

Robot Technology Development

Perception, User Interfaces and Architecture



Terry Fong

Intelligent Robotics Group
NASA Ames Research Center
terry.fong@nasa.gov

irg.arc.nasa.gov

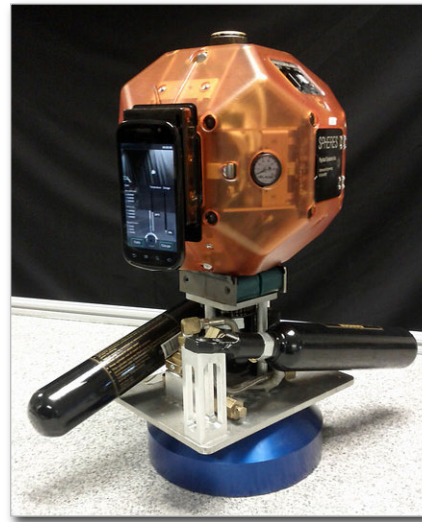
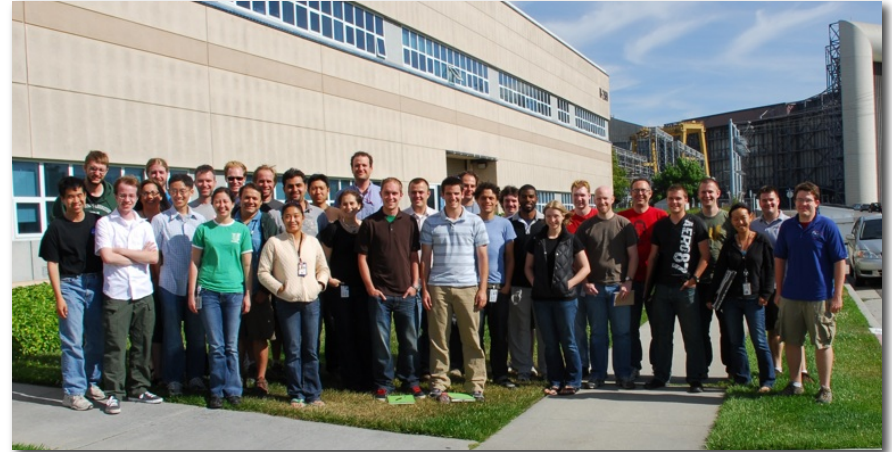
Intelligent Robotics Group (IRG)

Overview

- 31 researchers (14 Ph.D.'s)
- 20+ summer interns yearly
- 75% NASA work (HEOMD, STMD, SMD)
- 25% reimbursable (Google, etc.)
- SBIR / STTR (10 current proj.)

Research themes

- **Automated planetary mapping**
 - Base maps & terrain models
 - Geospatial data systems
- **Robots for human explorers**
 - Improve efficiency & productivity
 - Pre-cursor & “follow-up” work
- **Public service**
 - Disaster response & outreach



irg.arc.nasa.gov



IRG Collaborations (2010-2013)

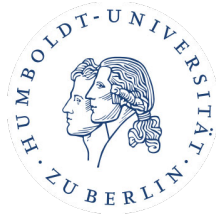
Academic



Massachusetts
Institute of
Technology



University of Idaho



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



Korea Advanced Institute of Science and Technology
한국과학기술원



Intelligent Robotics Group

Commercial



ProtoInnovations



Government



Robotics for Human Exploration

Purpose

- Increase human productivity
- Improve mission planning & execution
- Transfer **some** tasks to robots (tedious, repetitive, long-duration)

Before Crew

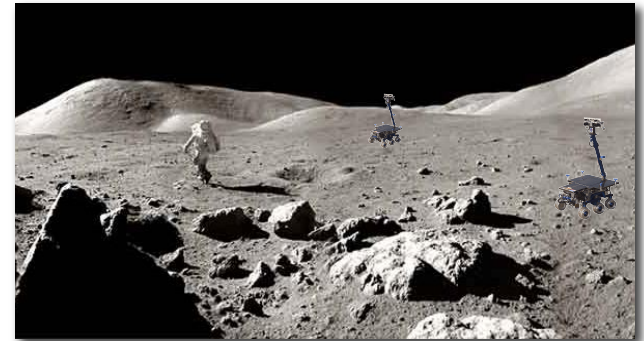
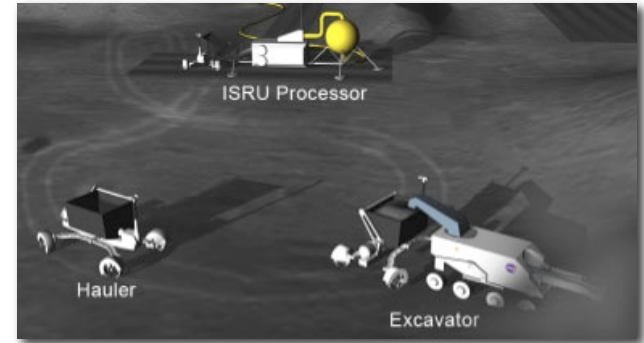
- Recon (scouting) & prospecting
- Site prep, deploy equipment, etc.

Supporting Crew

- Inspection, mobile camera, etc.
- Heavy transport & mobility

After Crew

- Follow-up & close-out work
- Site survey, supplementary tasks, etc.



Robots



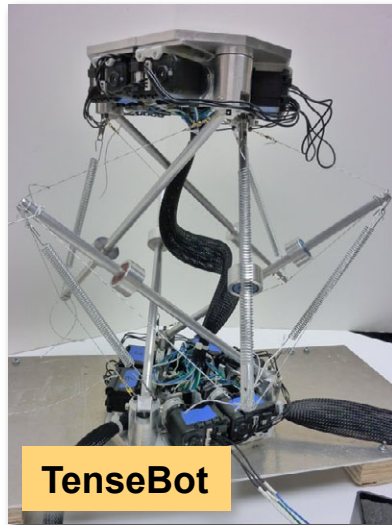
K10 mini



K10



KREX



TenseBot



Modular Arm



Smart SPHERES



GigaPan



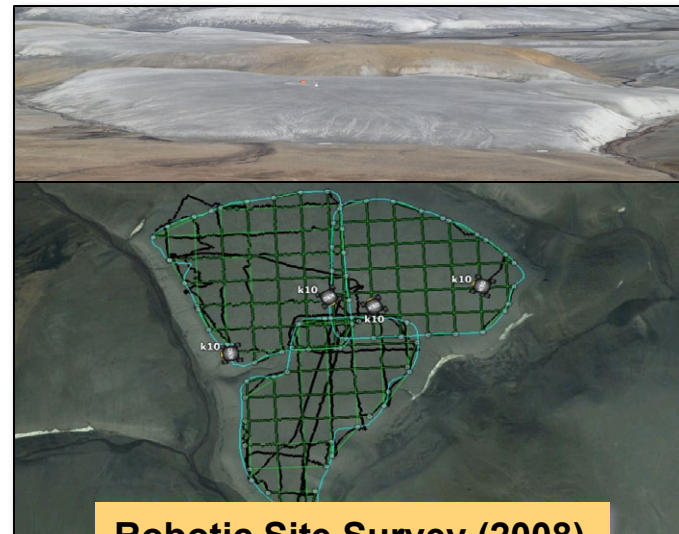
Lake Lander



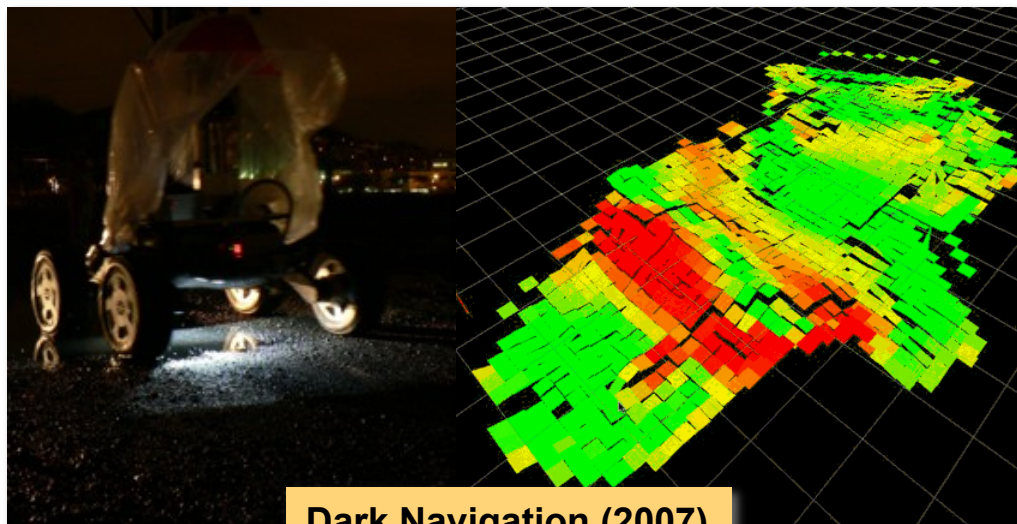
Perception



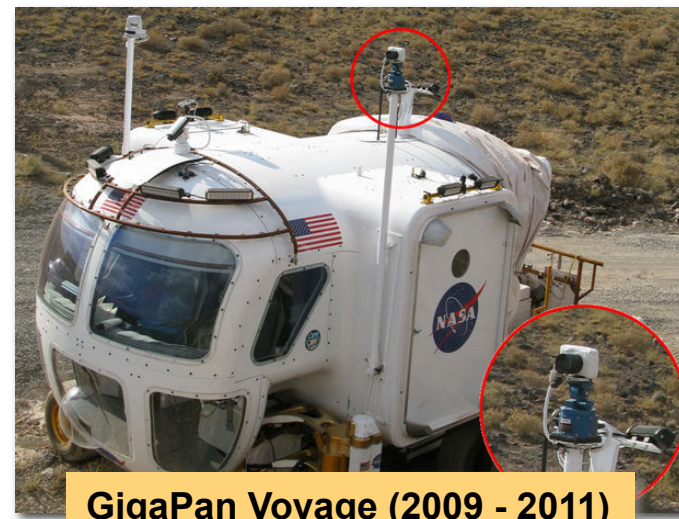
High Dynamic Range inspection (2006)



Robotic Site Survey (2008)

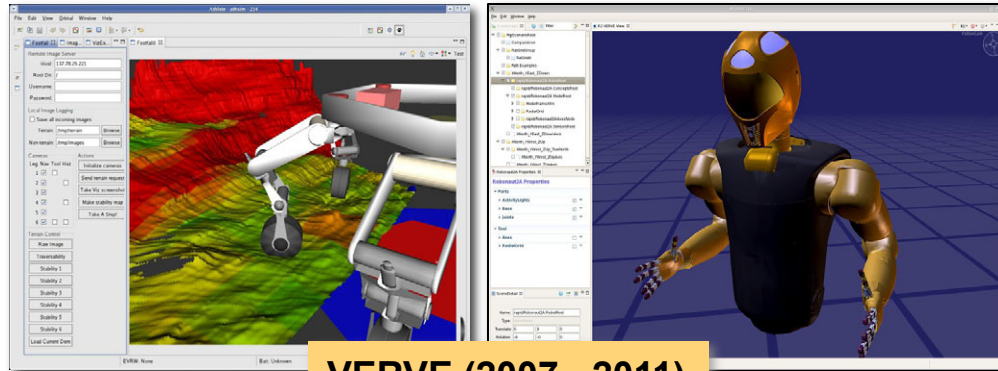


Dark Navigation (2007)

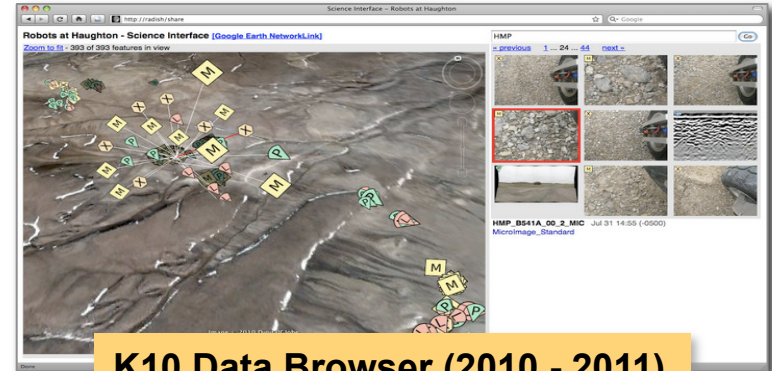


GigaPan Voyage (2009 - 2011)

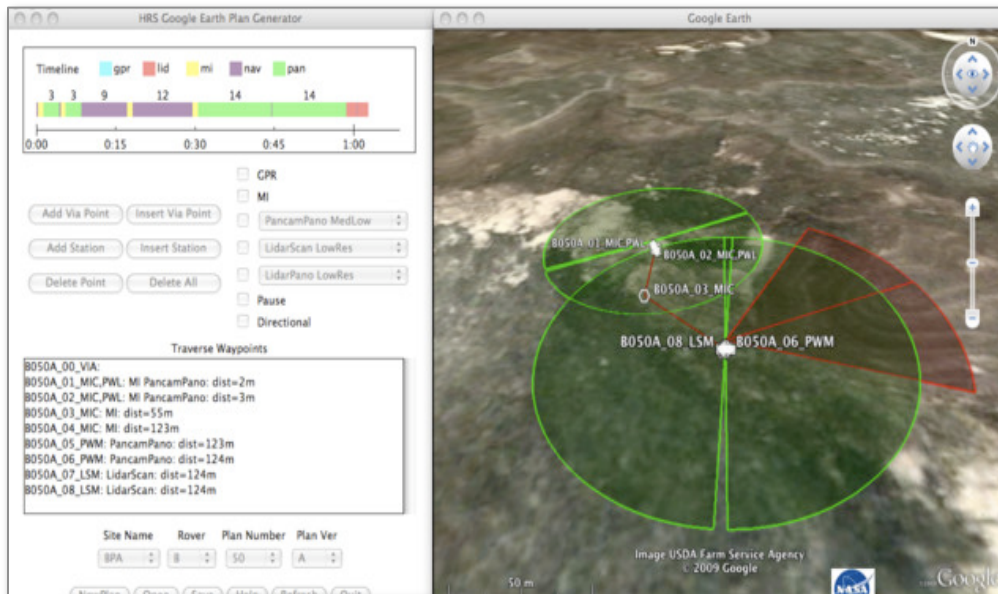
User Interfaces



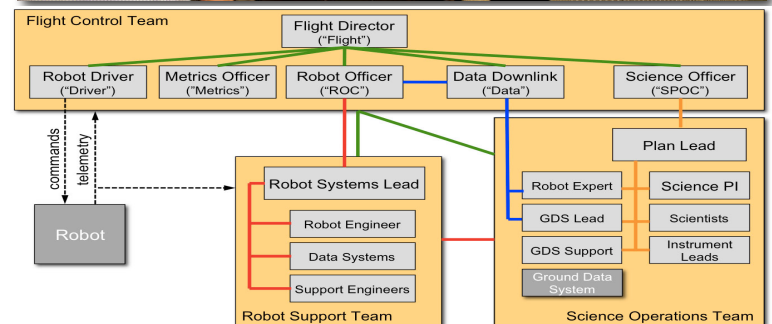
VERVE (2007 - 2011)



K10 Data Browser (2010 - 2011)



Google Earth Ops (2008 - 2011)

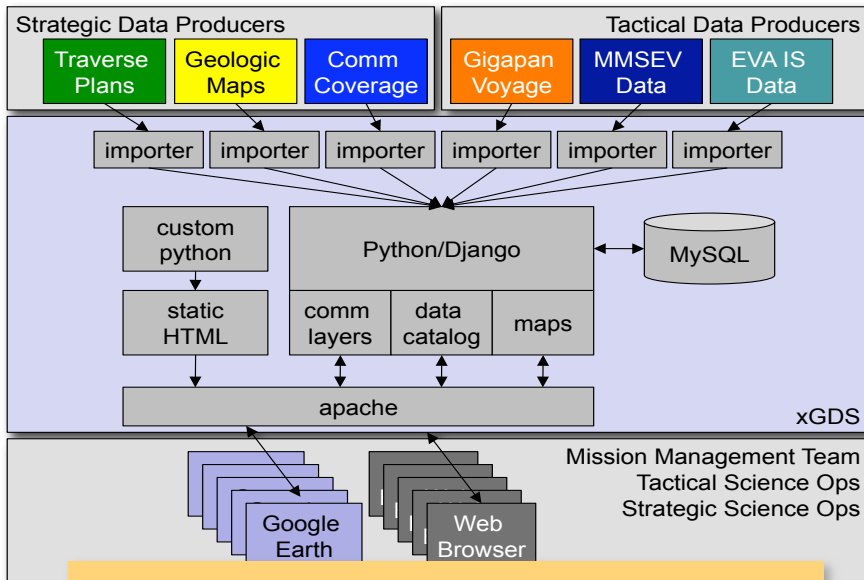
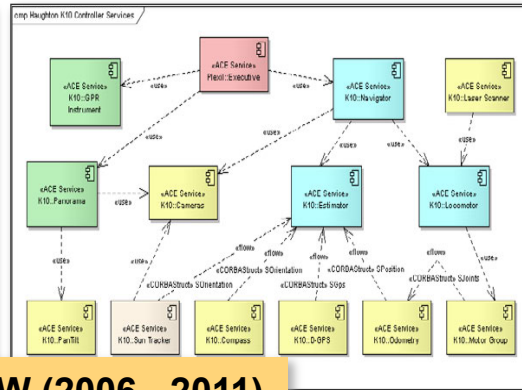


Interactive Ground Control (2008 - 2010)

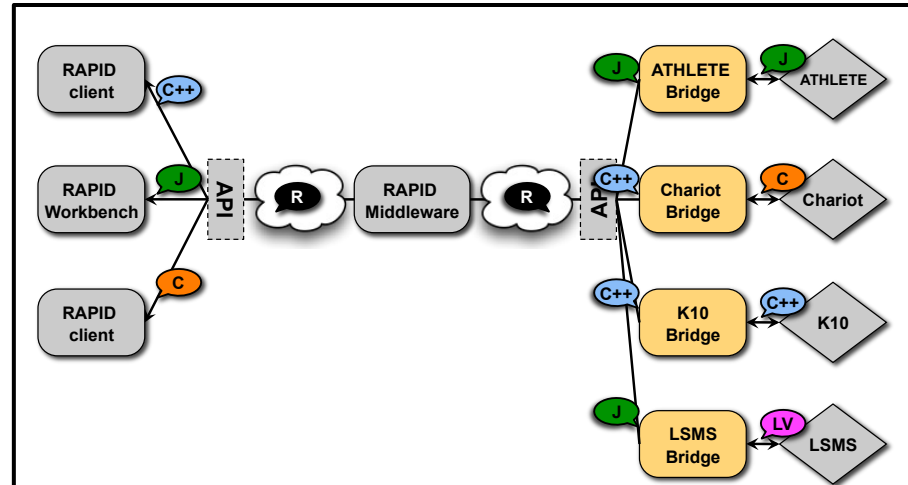
Architecture



RoverSW (2006 - 2011)



xGDS: Exploration Ground Data System (2009 - 2011)

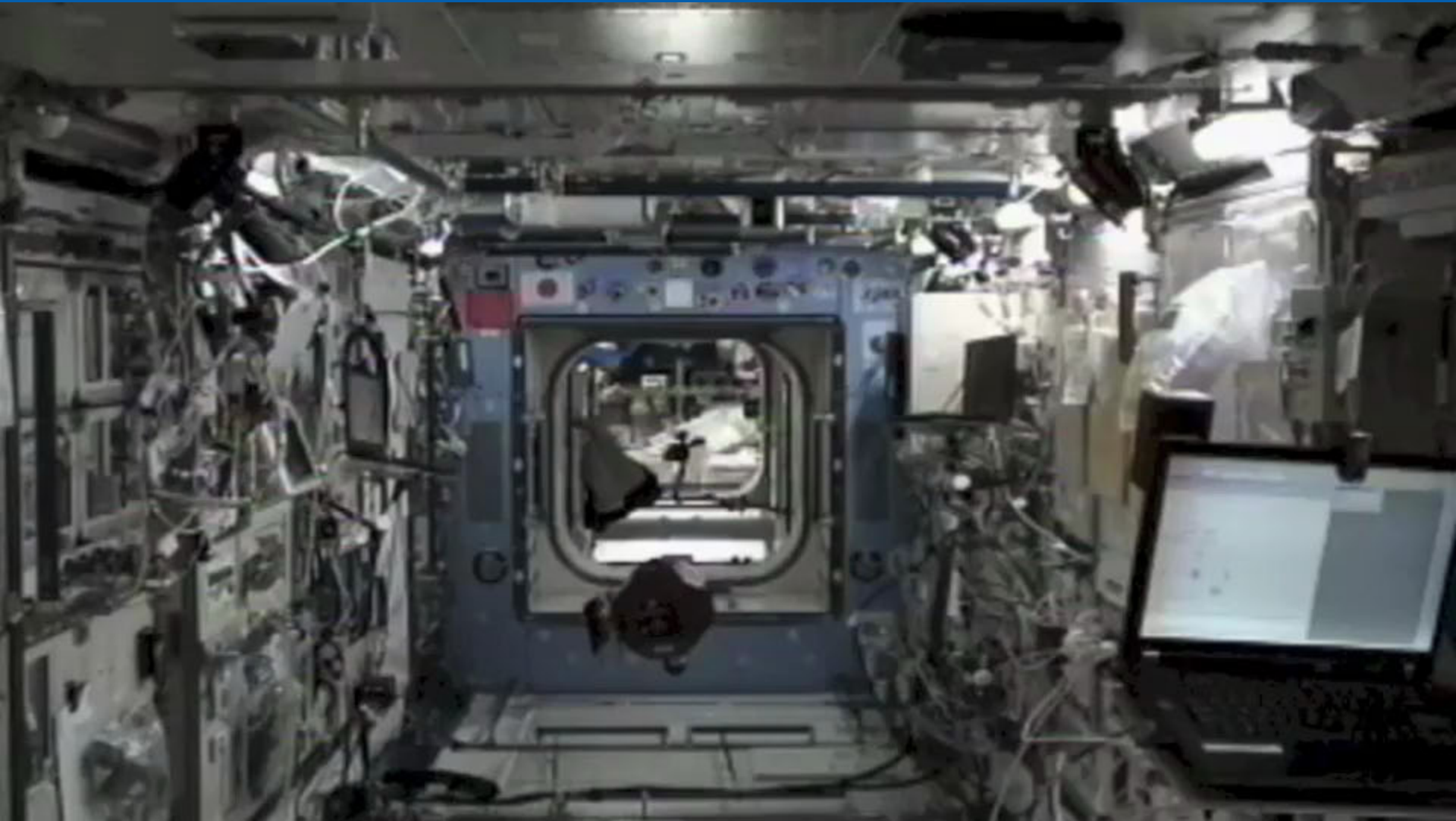


RAPID (2009 - 2011)

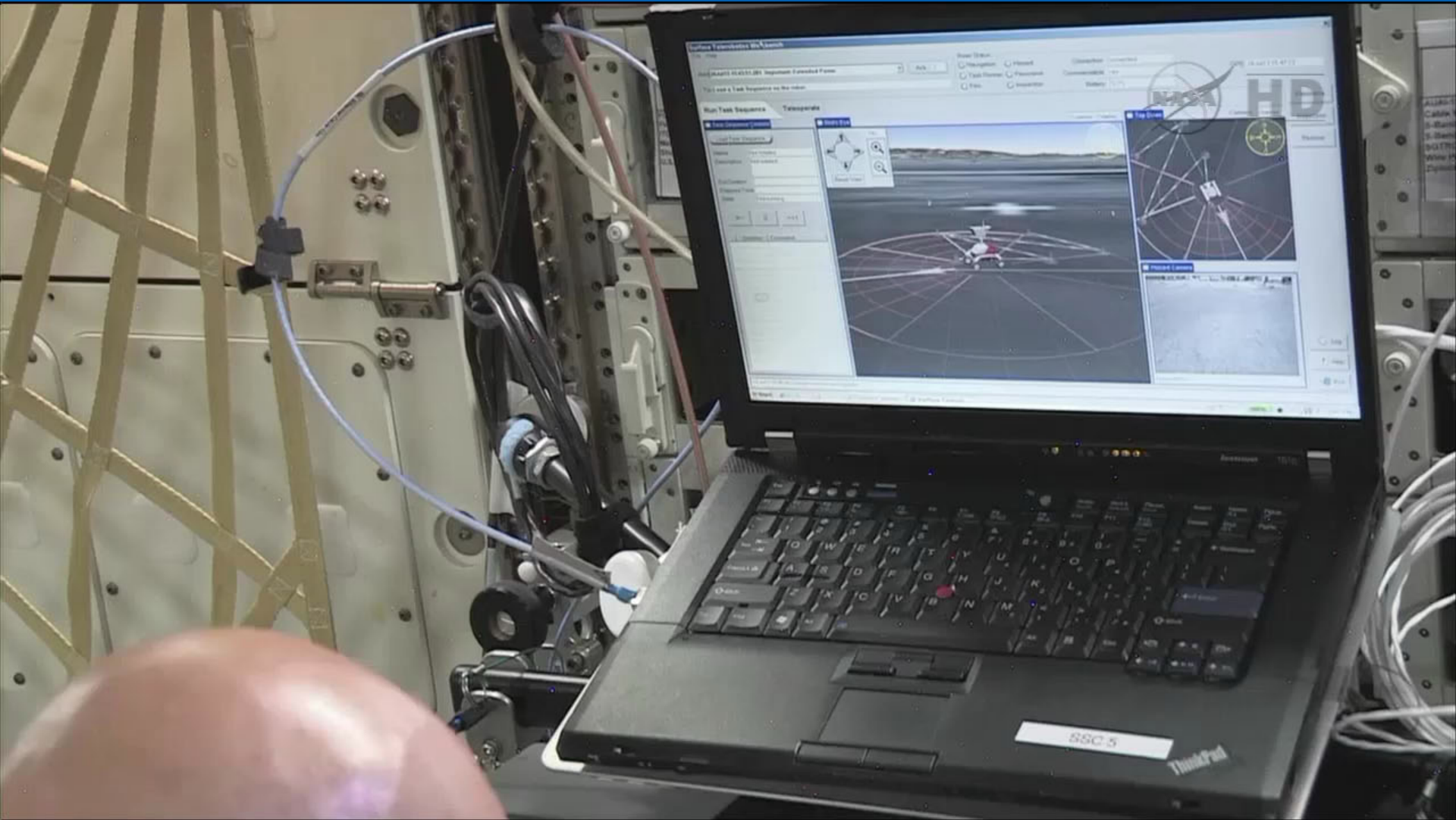
K10 Robot at Haughton Crater, Canada



SmartSPHERES on ISS



K10 Remotely Operated from ISS



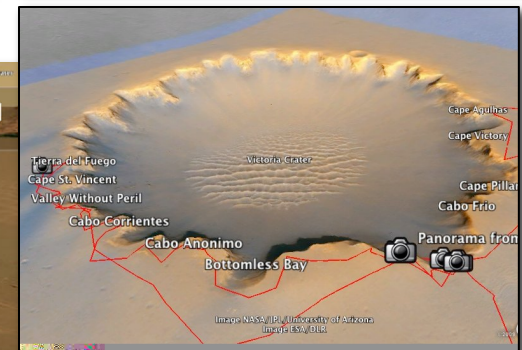
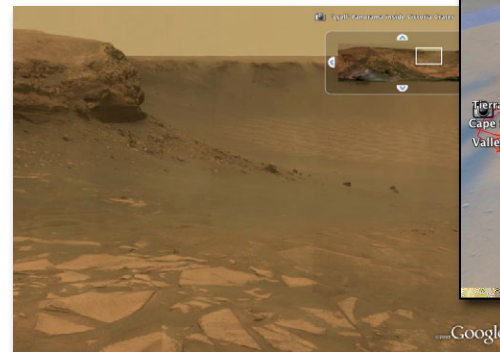
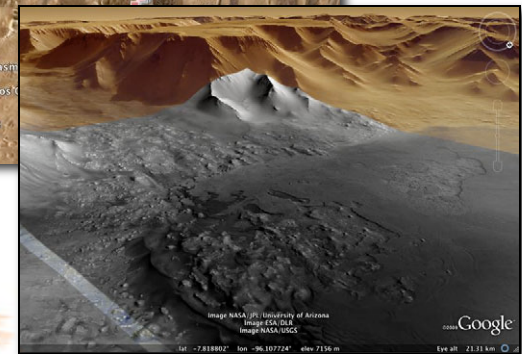
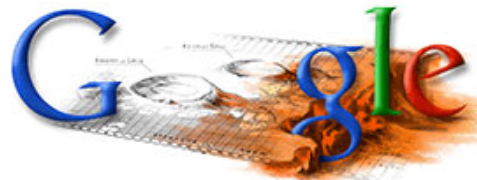
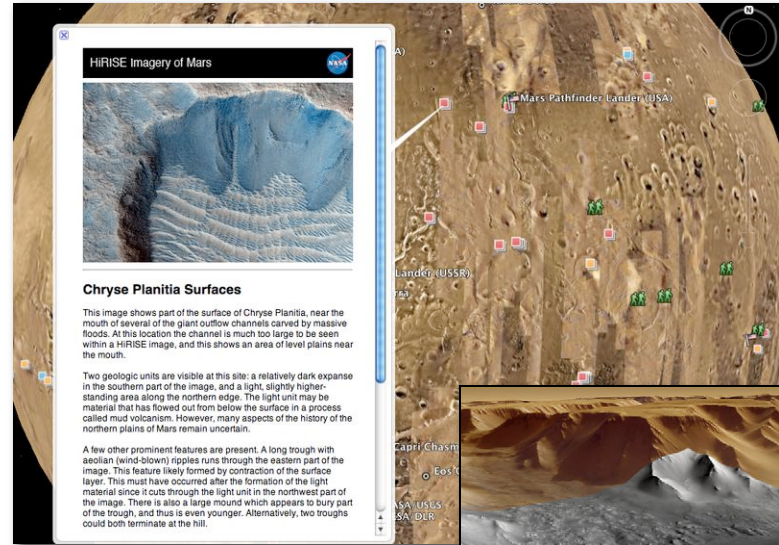
Mars in Google Earth

Explore Mars in 3D

- Released Feb. 2, 2009
- Co-developed with Google
- NASA Ames created content & processing scripts

Content

- Global maps: topography, infrared, historical, etc.
- Imager footprints & overlays (HiRISE, CTX, MOC, ...)
- Mars rover tracks & color panoramas
- Tours (Bill Nye & Ira Flatow)
- Live from Mars: THEMIS
- And much more ...



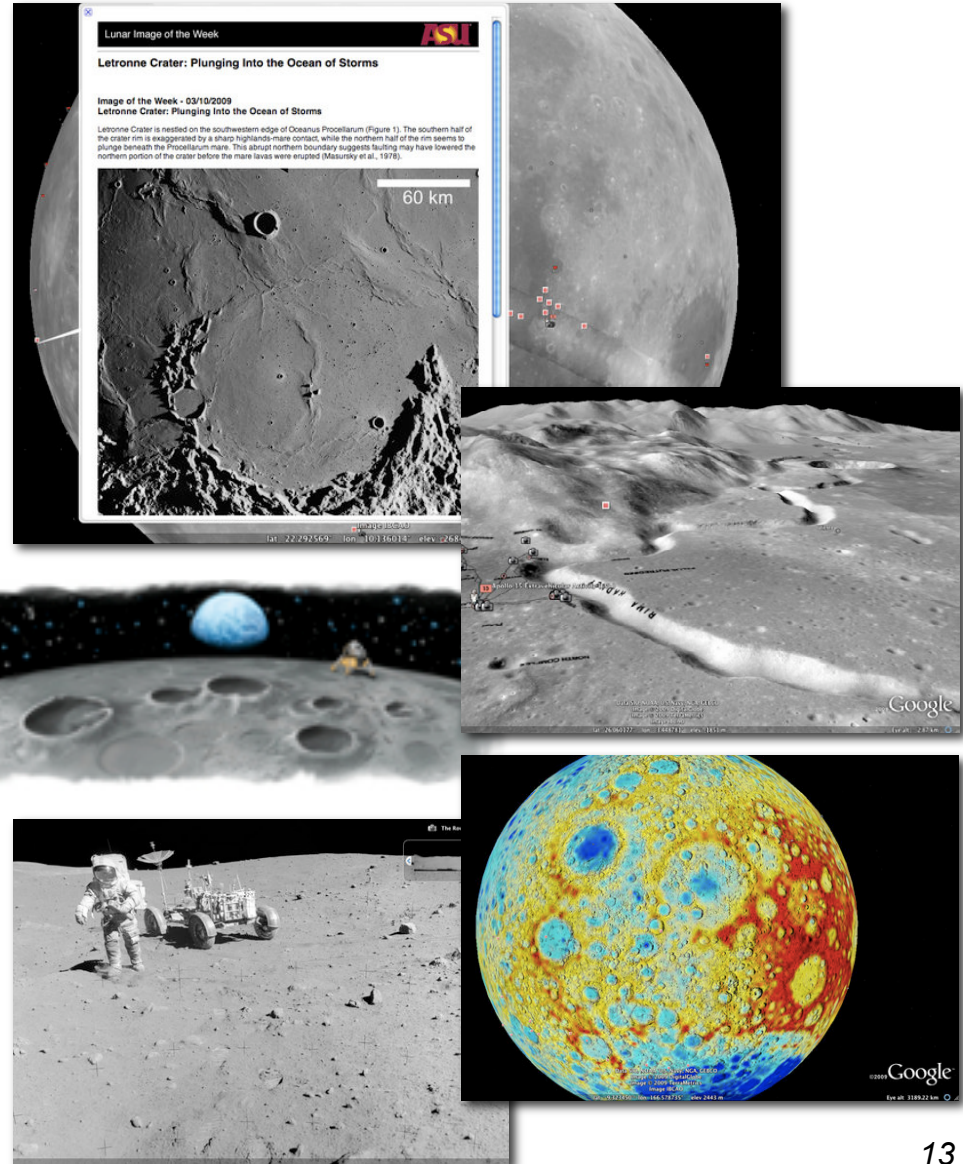
Moon in Google Earth

Explore the Moon in 3D

- Released July 20, 2009
- Co-developed with Google
- NASA Ames created content & processing scripts

Content

- Global maps: topography, geologic, historical, etc.
- Spacecraft imagery: Apollo, Lunar Orbiter, etc.
- 3D models of spacecraft, landers, and crew rovers.
- Tours (Andy Chaikin, Buzz Aldrin & Jack Schmidt)
- And much more ...



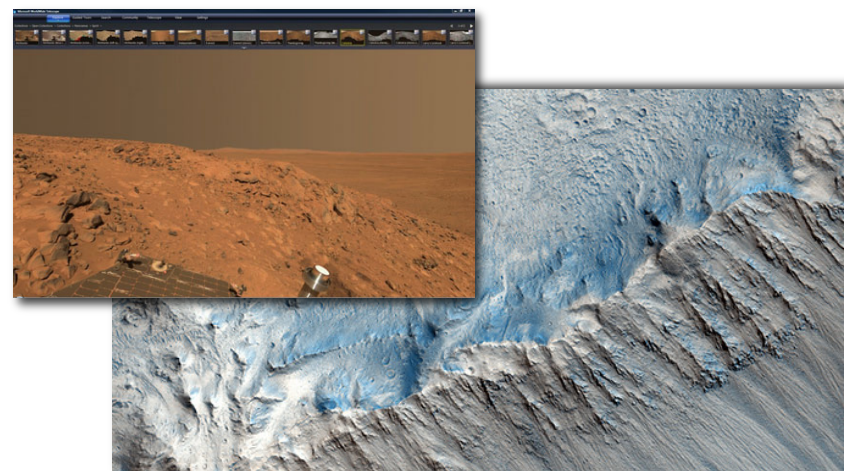
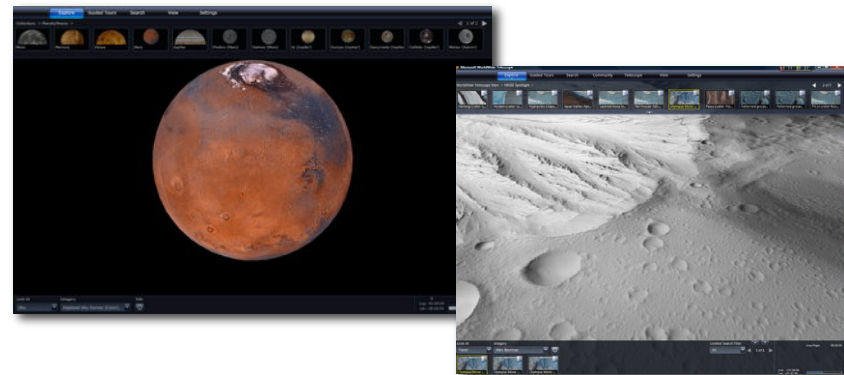
WorldWideTelescope | Mars

Complete HiRISE Mosaic

- Mars Reconnaissance Orbiter HiRISE imager
- 74,000 images
- Each image: 20K x 50K pixels (> 1 GB / image)

Mosaic stats

Tile Dimensions	256 x 256 pixels
Root Tiles / Image	15,000
Tile Space	25 KB
Tiles Total	229 million
Total Mosaic Size	5.7 TB



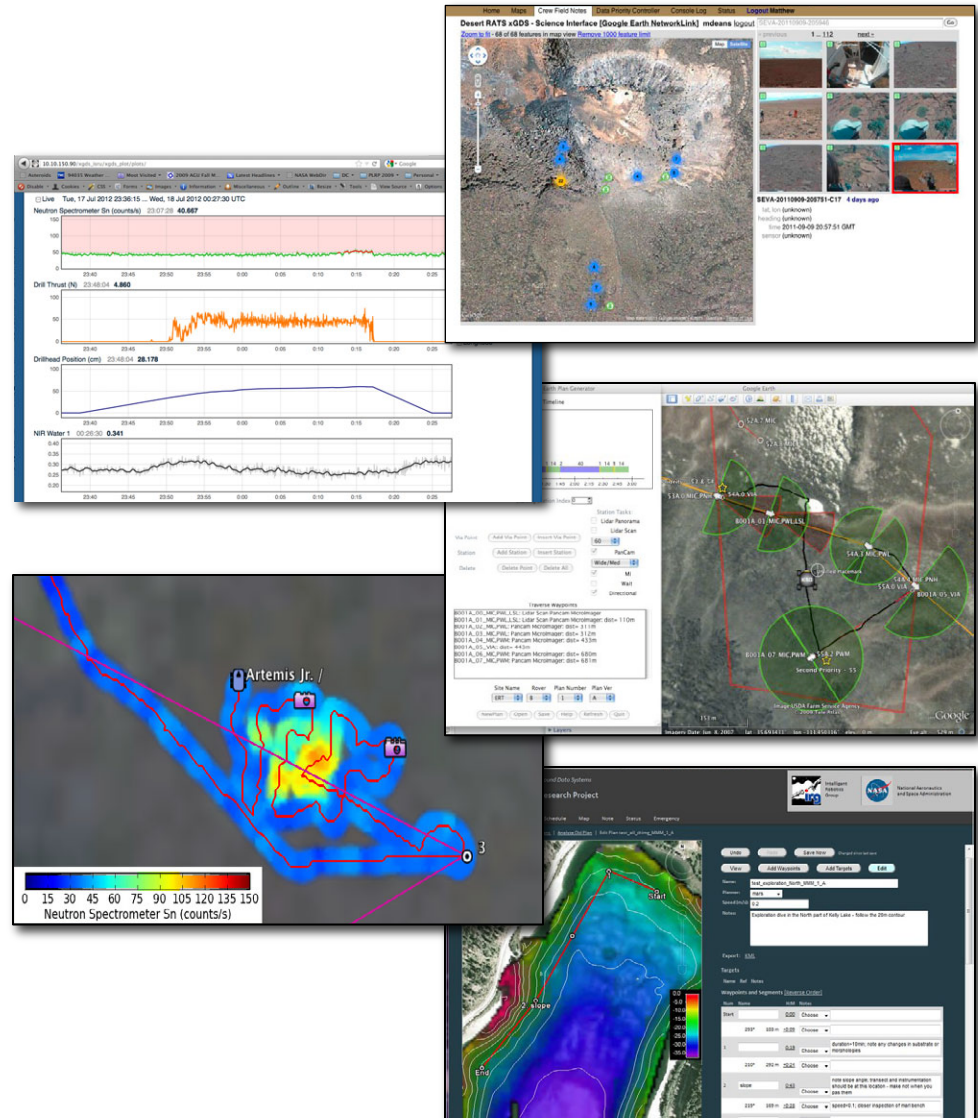
Exploration Ground Data System (xGDS)

xGDS is ...

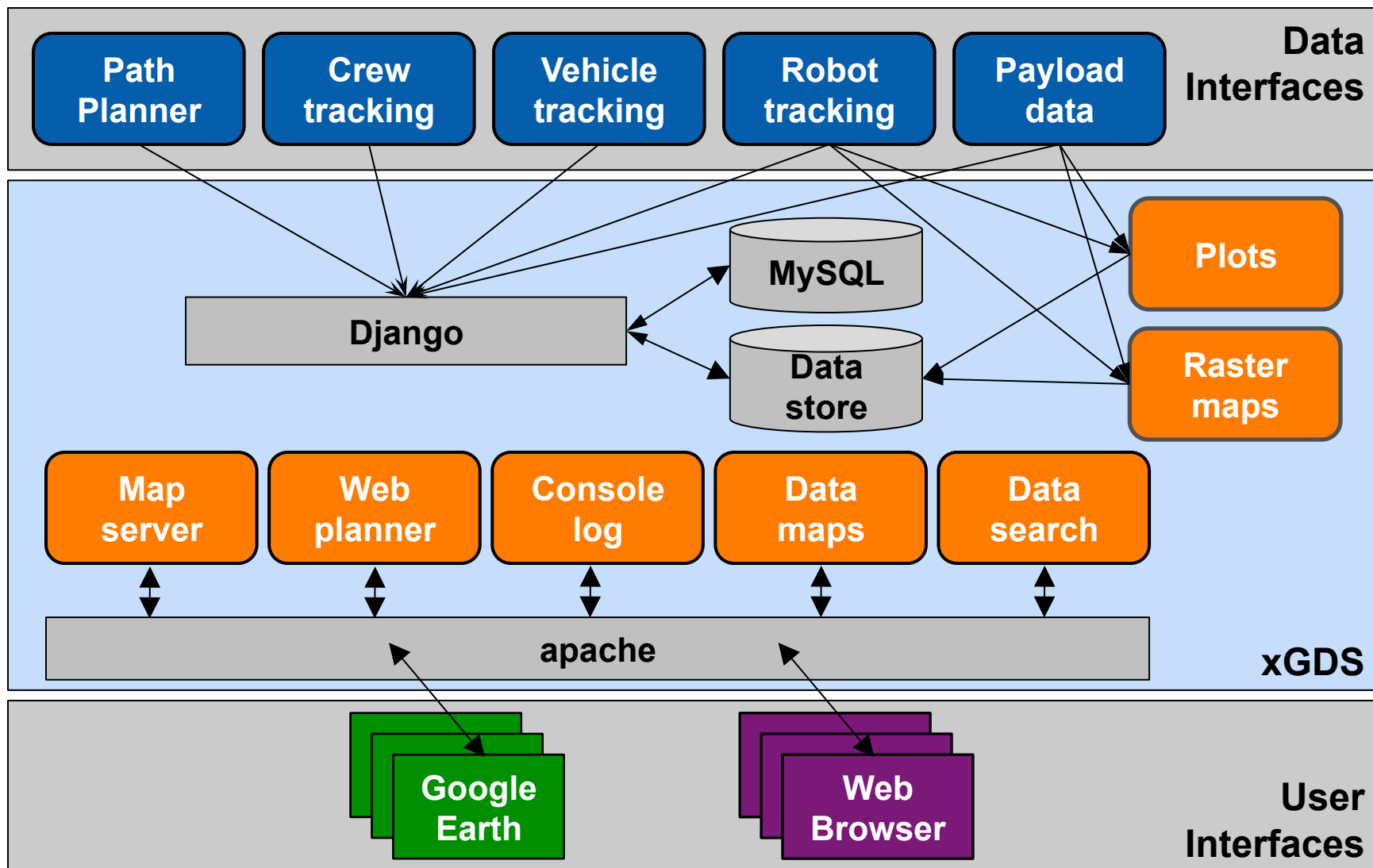
- Map content management
- Planning tool
- Real-time plots, maps, notes
- Post-processing data archive
- Browse and search tools

Users

- Field scientists
- Planetary scientists
- Mission planners
- Flight controllers
- Local & distributed teams

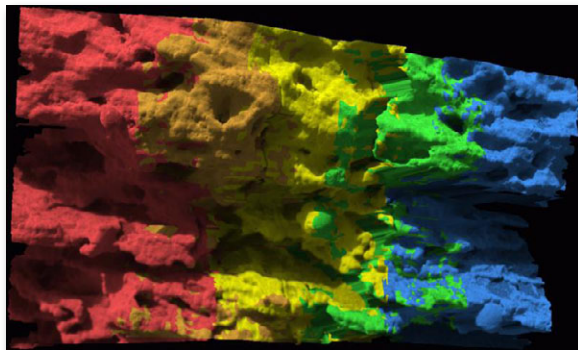


xGDS Architecture

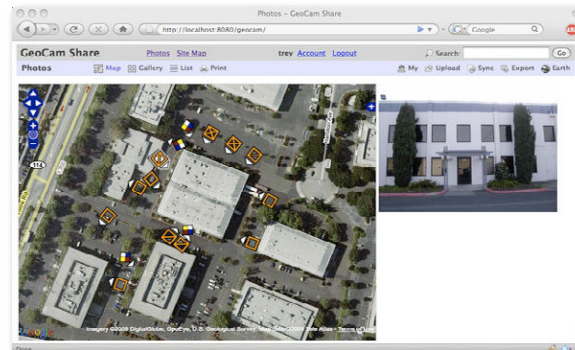


IRG Open Source Software

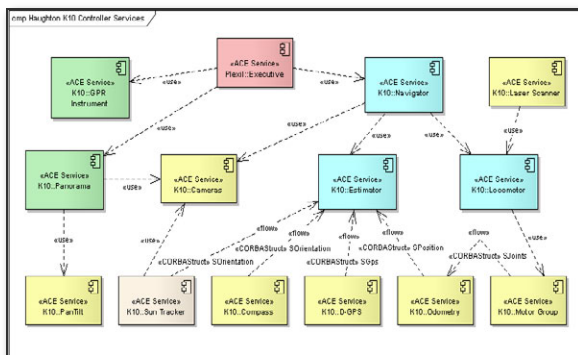
Vision Workbench



Exploration Ground Data Systems (**xGDS**)



RoverSW

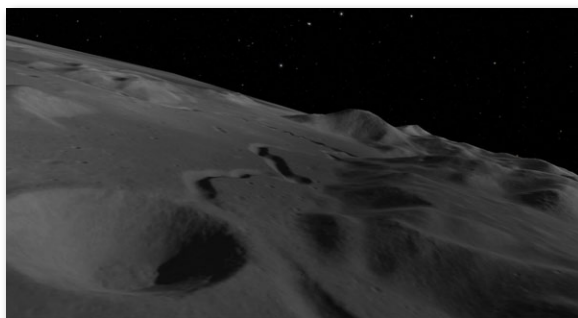


Visual Environment for Remote Virtual Exploration (VERVE)

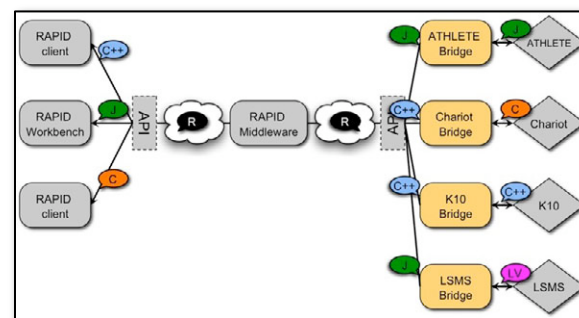


Neo Geography Toolkit

(with Ames Stereo Pipeline)



RAPID
(NASA robot
middleware)



Questions?



Intelligent Robotics Group

Intelligent Systems Division
NASA Ames Research Center

irg.arc.nasa.gov



NASA Ames Planetary Mapping

Making NASA's data more rapidly and universally available



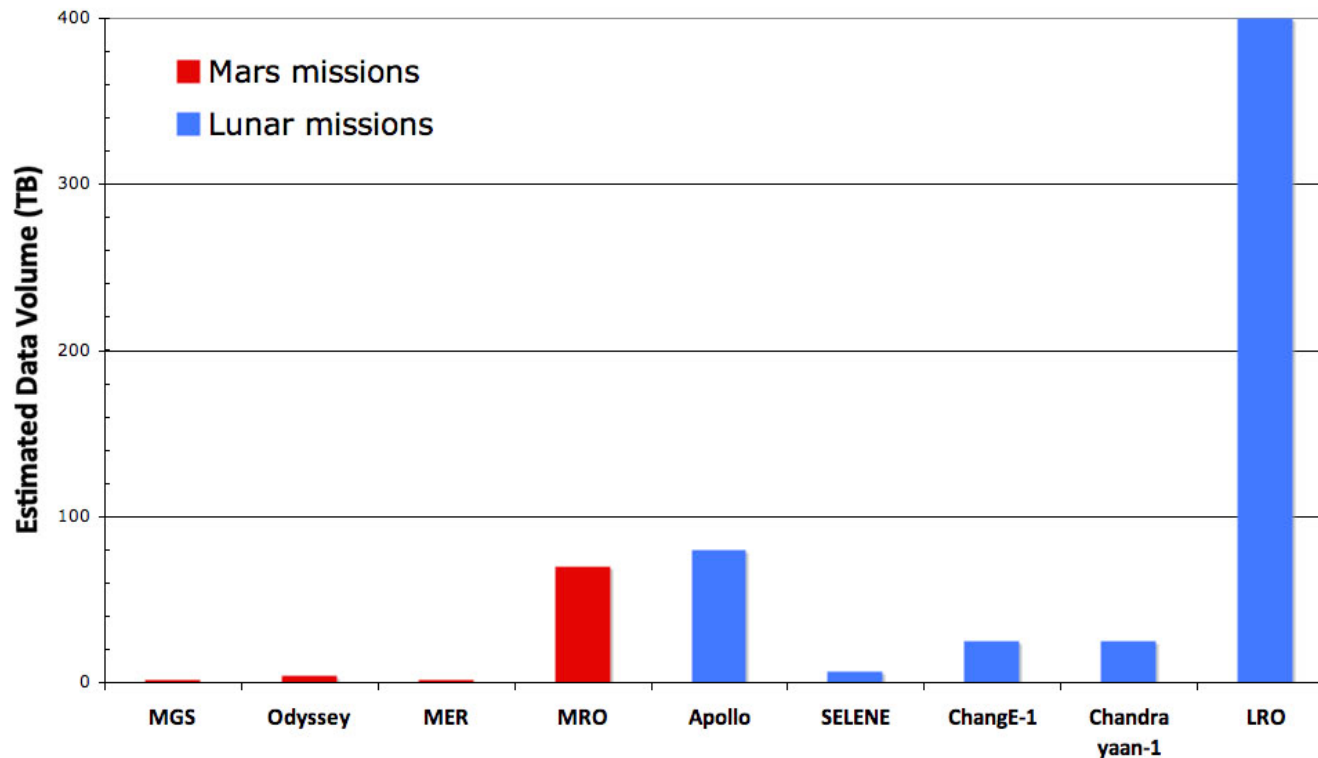
<http://irg.arc.nasa.gov>
Intelligent Robotics Group
NASA Ames Research Center

Contact: terry.fong@nasa.gov

Really Big Data

Why do we need to build *automated systems* to handle large volumes of Planetary data?

We are in the midst of a major geospatial information explosion. For the first time, 10's of Terabytes of map data are being collected by robotic explorers.



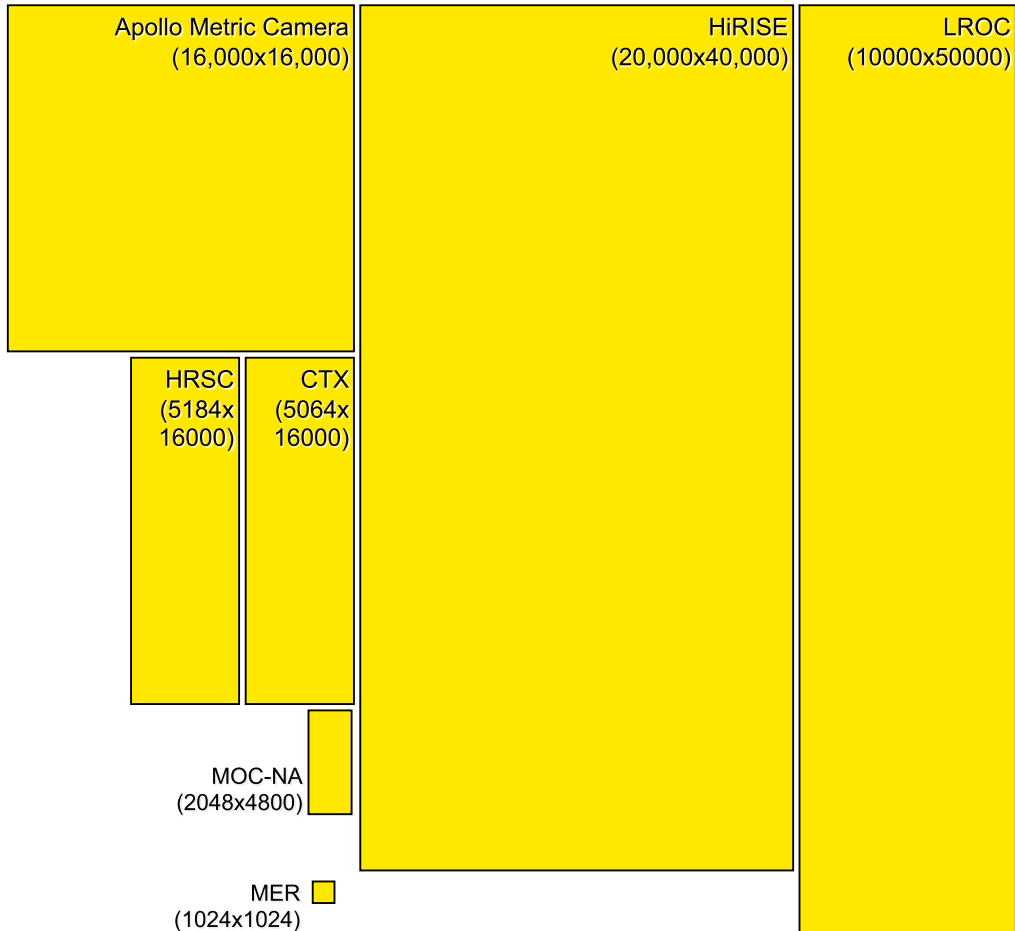
Approximate data volumes from various Mars (red) and Lunar (blue) missions.

Data volumes are in Terabytes!

Source: B. A. Archinal, L. R. Gaddis, R. L. Kirk, T. M. Hare, and M. R. Rosiek. [Urgent Processing and Geodetic Control of Lunar Data](#). Workshop on Science Associated with the Lunar Exploration Architecture, 2007.

Really Big Images

Why do we need to build *automated systems* to handle large volumes of Planetary data?



Nominal Resolutions for Various Imagers. All sizes given in pixels.
Apollo Panoramic Camera film scans are not shown (25400 x 244000 pixels)!

- In the past, widely used maps such as the Viking MDIM mosaic took *years* to produce.



- Today, *human intensive processes can be automated* so that data can be processed & distributed more rapidly.

Some of our Projects

Automated 3D surface reconstruction, mosaicking, gigapixel imaging

- Bridging the gap between PDS and Geo-browser platforms

Enabling faster, easier, and universal access

- Developers in the Lunar Mapping and Modeling Program (LMMP)

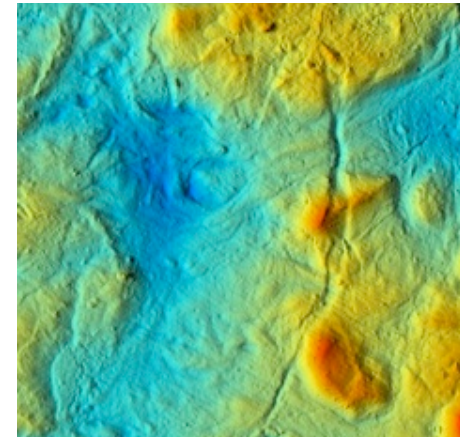
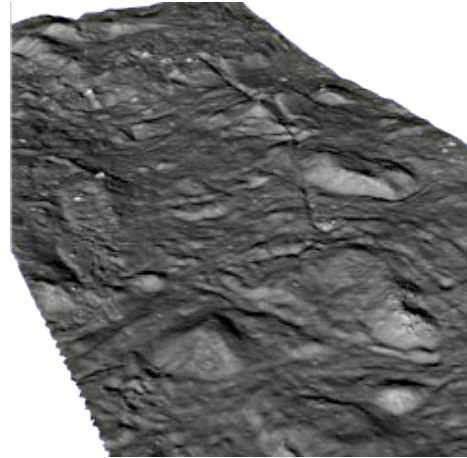
Providing stereo-derived topography and imagery from Apollo Metric Camera scans

- LROC & HiRISE Team Members

Validating and estimating the errors of LROC-derived DTMs

- Assorted other projects:

Vision Workbench, Ames Stereo Pipeline, Neo-Geography Toolkit, Small body mapping



Automated Stereo Reconstruction of Jackson Crater (LROC)



**Human and Robotic Mission
to Small Bodies:
Mapping, Planning and Exploration**

**A Study for the Advanced Exploration Systems
(AES) Joint Robotic Precursor Activities (JRPA)
Project**

*Ara V. Nefian
Carnegie Mellon University, Moffett Field, California*

*Julie Ballerose
Carnegie Mellon University, Moffett Field, California*

*Ross A. Beyer
SETI Institute, Mountain View, California*

*Laurence Edwards
Ames Research Center, Moffett Field, California*

*Pascal C. Lee
Mars Institute, Moffett Field, California*

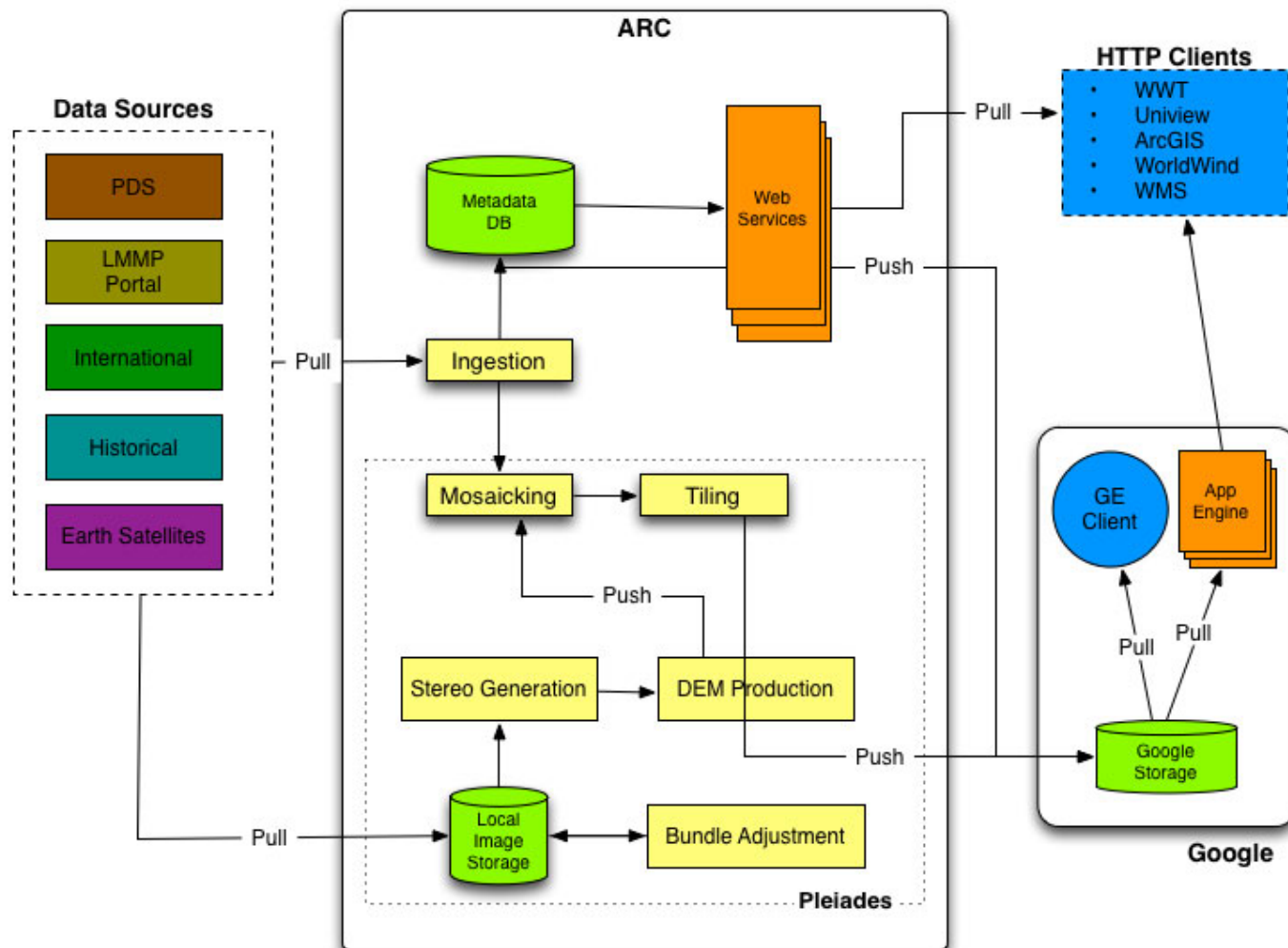
*Anthony Colaprete
Ames Research Center, Moffett Field, California*

*Terrence Fong
Ames Research Center, Moffett Field, California*

Our Automated Pipeline

Unified architecture for processing & serving planetary data through web services

- Our geospatial data pipeline has been developed to **automatically produce** high-quality planetary maps and models
- It is extremely **flexible & extensible**, supporting many data source and open standards & protocols.
- Our software stack **runs on Pleiades**, the NASA Ames supercomputer

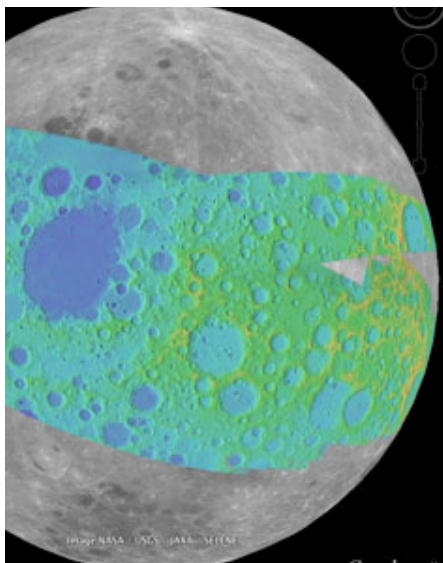


Ames Stereo Pipeline

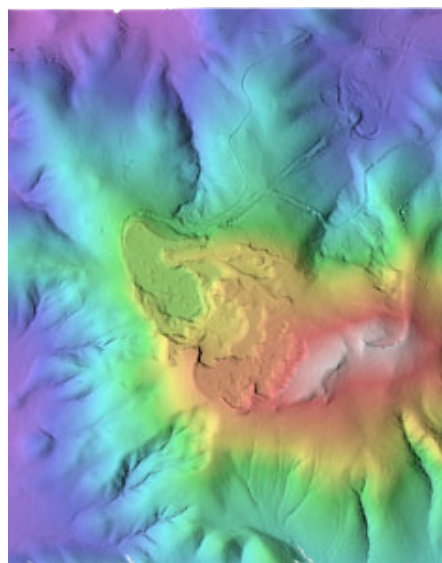
Open-source automated stereogrammetry software



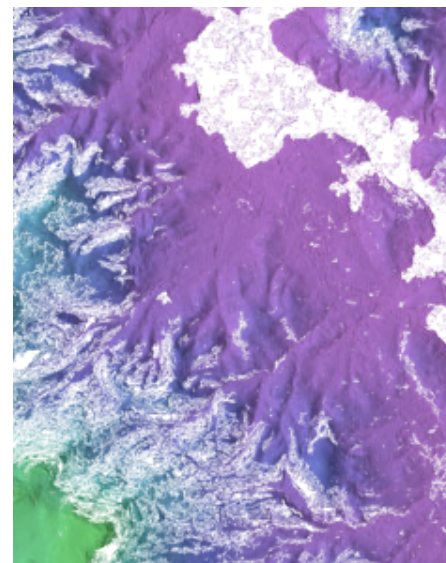
Models from traditional stereo cameras using the **TSAI** format.



Models of the other planets using USGS's **ISIS** cube files.



Models of Earth using **Digital Globe** Stereo 1B imagery.

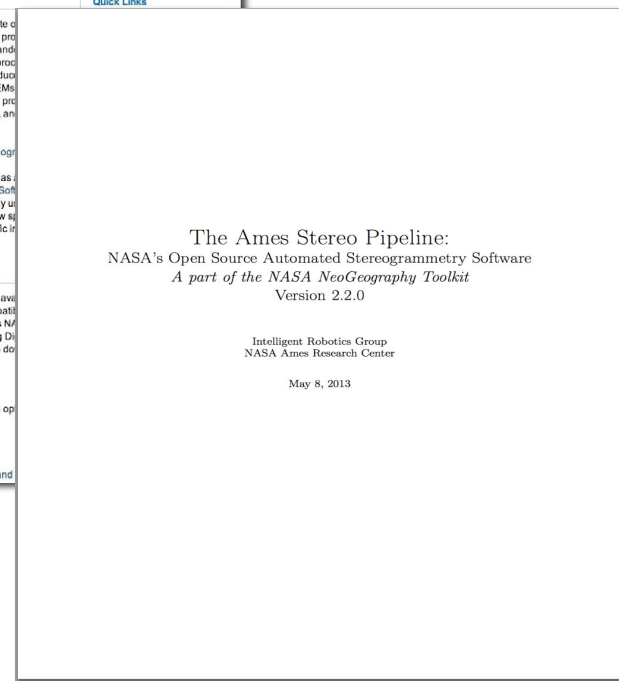
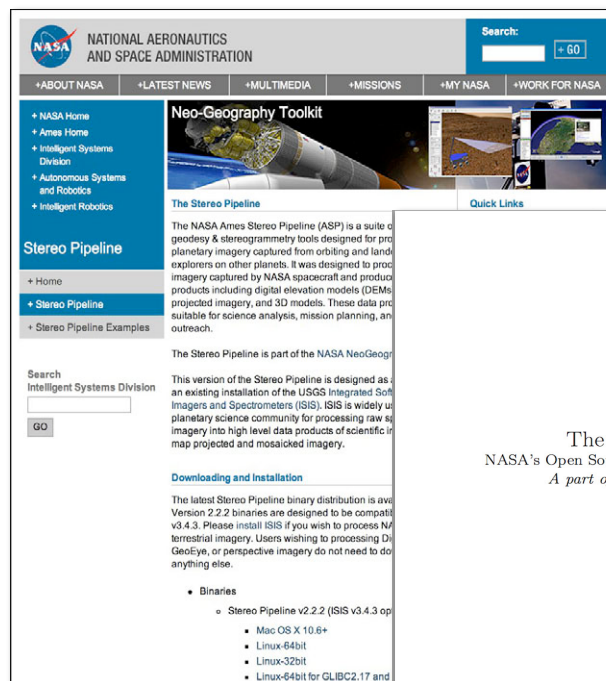


Models of Earth using imagery that contains an **RPC** Model.

Ames Stereo Pipeline (ASP)

Open-source automated stereogrammetry software

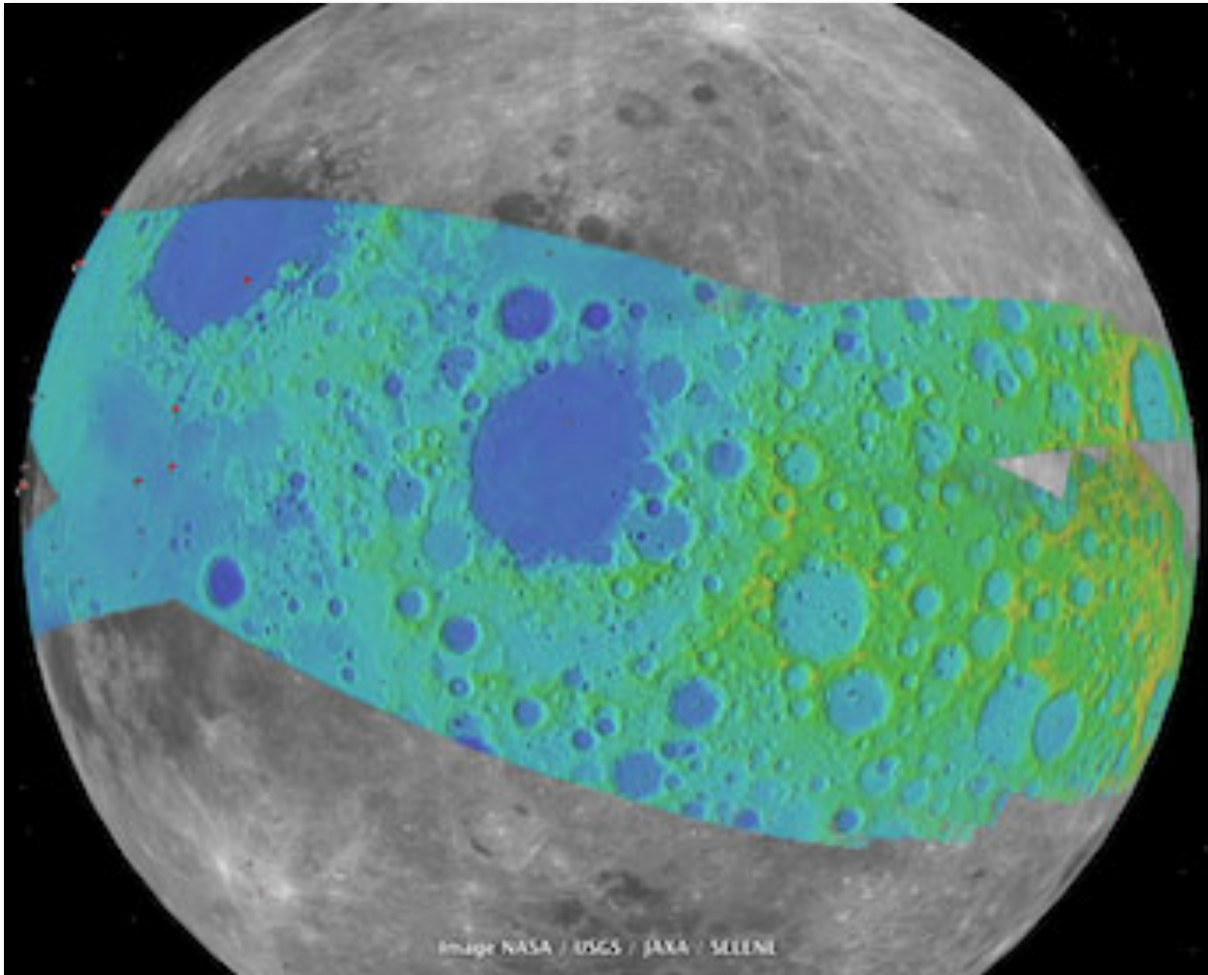
- What it is...
 - Command-line tools for computing clusters and super computers
 - C++ code hosted on GitHub
 - Binaries available for Linux and OS-X
 - Apache 2 license
- Data processed with ASP
 - Apollo Metric Camera
 - Digital Globe IB products
 - Lunar Reconnaissance Orbital Camera (LROC-NA)
 - Mars High Resolution Imaging Science Experiment (HiRISE)
 - Mars Orbiter Camera (MOC)
 - MRO Context Camera (CTX)



tiny.cc/ames-stereo-pipeline

Apollo Zone DEM

High-resolution terrain model (digital elevation map)



- Mosaick of 4,000 images
 - Apollo Metric Camera
 - 73,728 x 368,640 pixels
- Equatorial Lunar Surface (38S-34N lat)
 - 1,024 pixel / deg
 - Vert. acc 40.9m (LOLA)
 - Vert. stdv 37.8m
 - Horiz. acc 91.3m (LOLA)
- Controlled to LOLA through LRO-WAC
- 40,000 CPU hours (4 days on NASA Pleiades)

Albedo Reconstruction

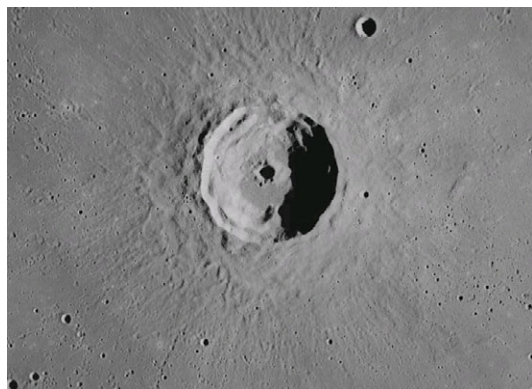
Scalability from single core to super computer (GNU parallel)

- **Image formation model:**

Camera Transfer Function, Albedo, Exposure Estimation, Surface Reflectance, and Shadow

- For the Moon, uses Lunar-Lambertian Model (can be extended to non-Lunar surfaces) to reduce the effect of varying illumination

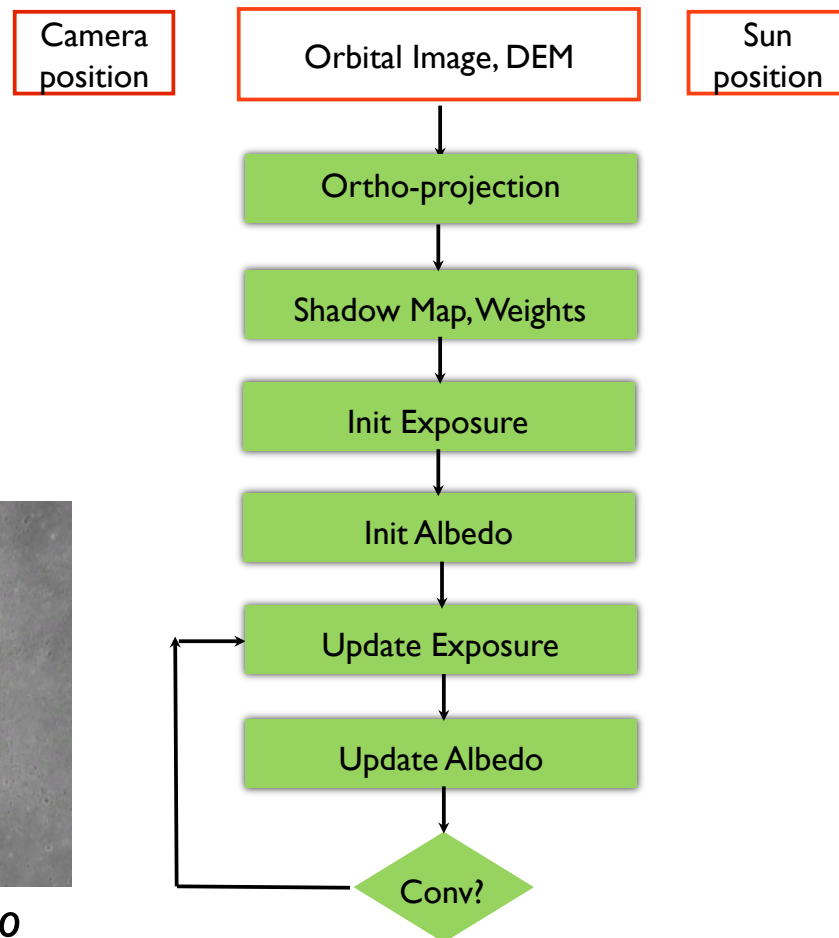
- Overlapping images allows for shadow removal



Original



Reconstructed albedo



Albedo Reconstruction

Hadley Rille (Apollo Metric Camera images)



Original



Reconstructed albedo

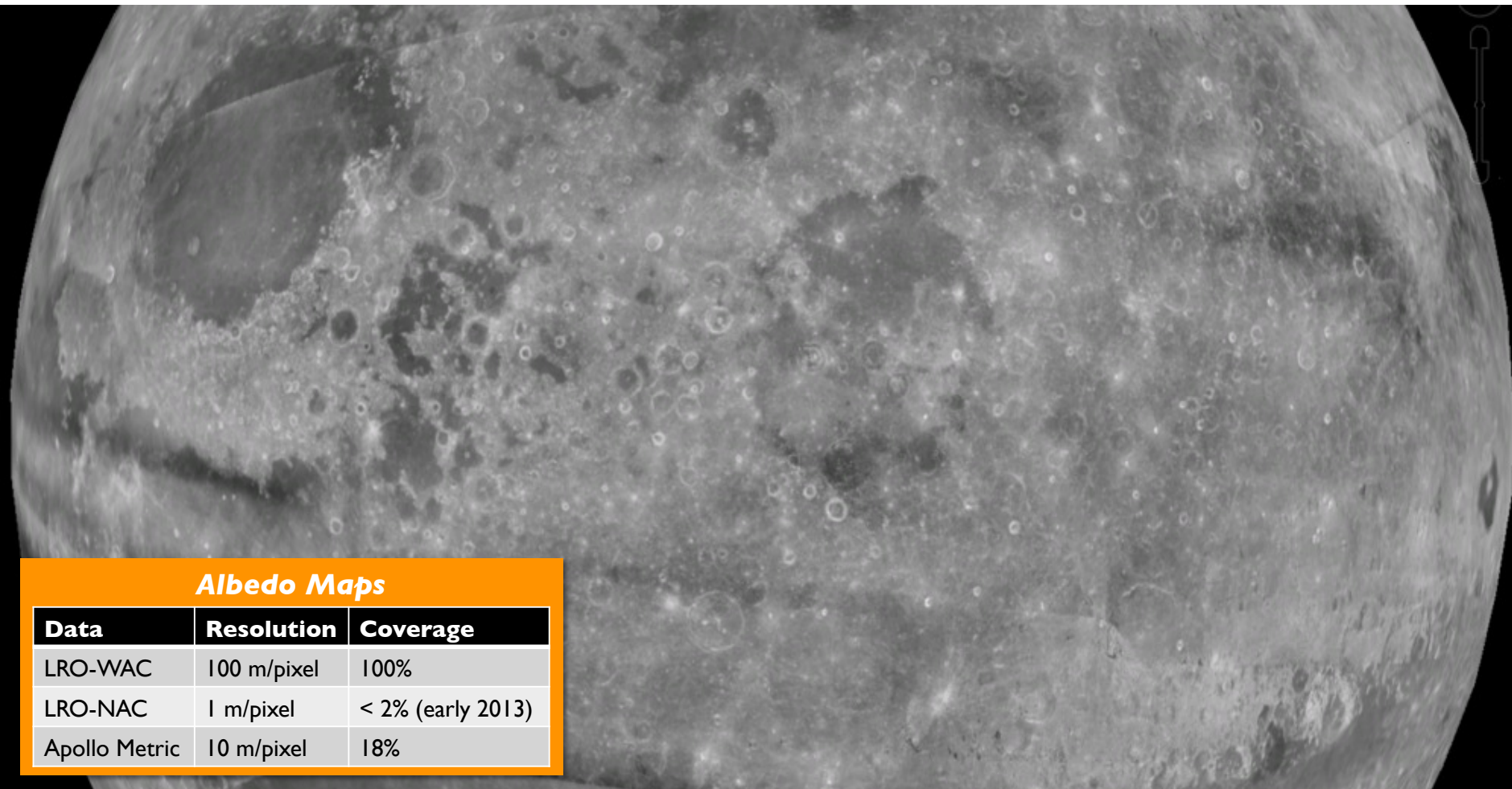
Albedo Reconstruction

Hadley Rille (Apollo Metric Camera images)



Apollo Zone DIM

High-resolution base map (digital image mosaick)

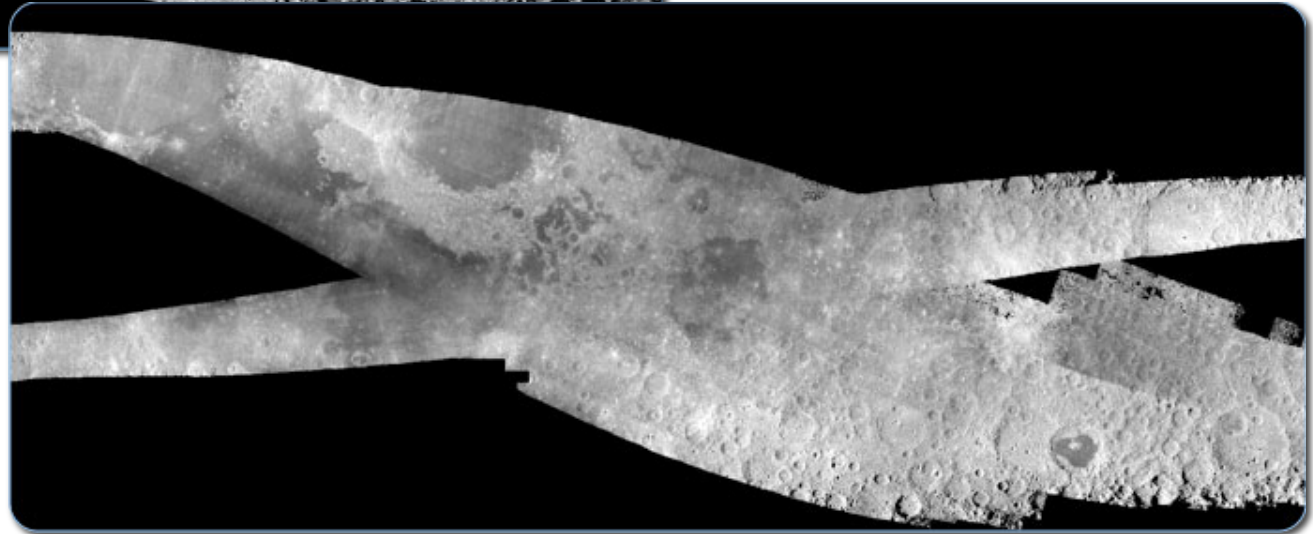
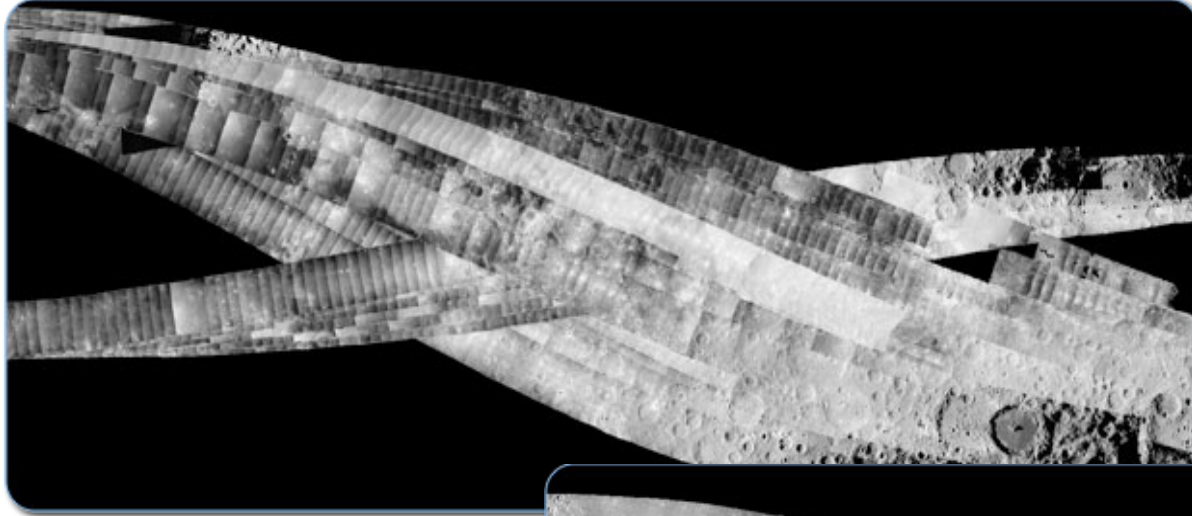


Albedo Maps

Data	Resolution	Coverage
LRO-WAC	100 m/pixel	100%
LRO-NAC	1 m/pixel	< 2% (early 2013)
Apollo Metric	10 m/pixel	18%

Mosaicking & Blending

Highly accurate reconstruction, blending, and error modeling



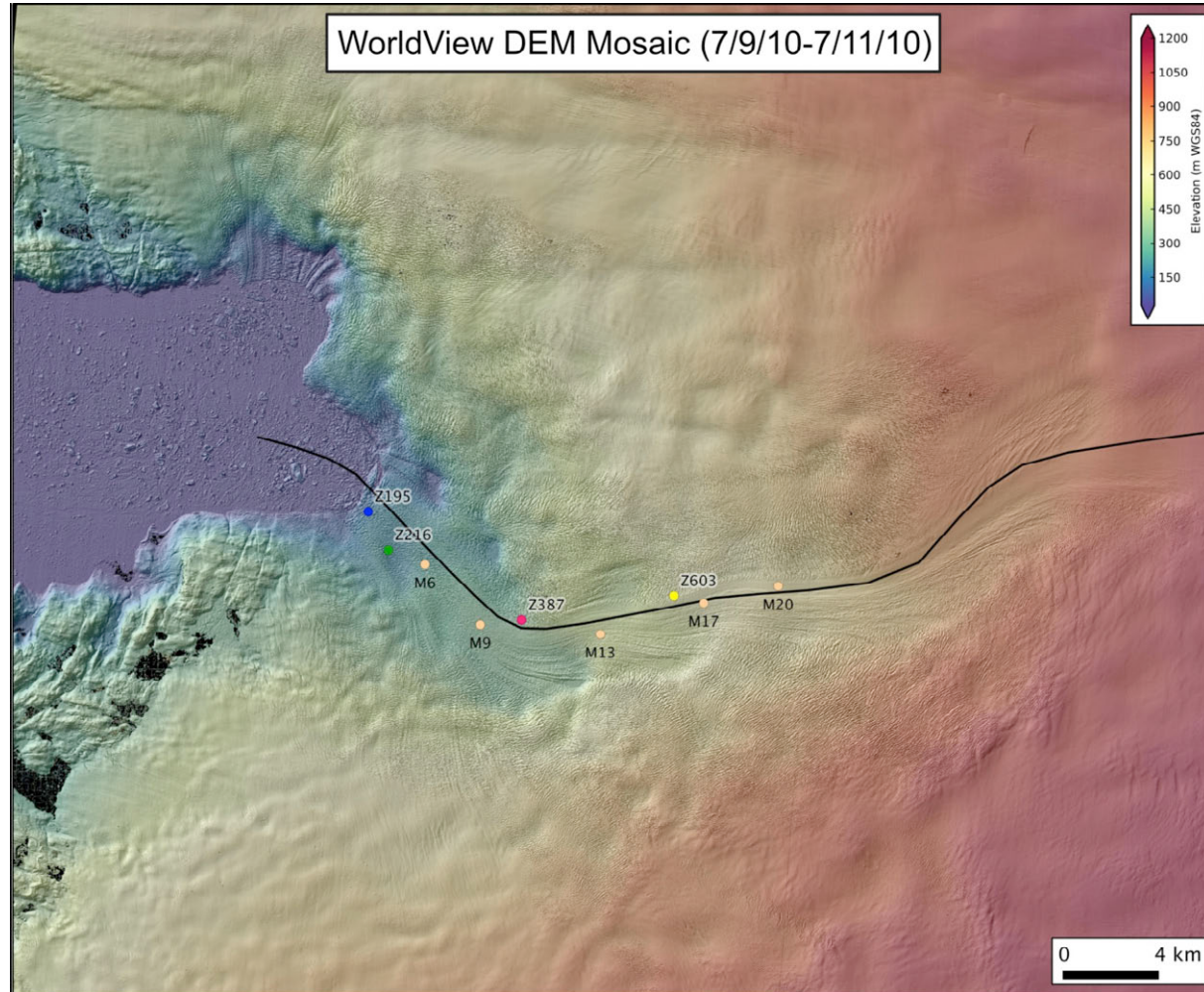
ASP for Earth

Cryospheric mapping for Earth science (glaciology, climate change, etc)



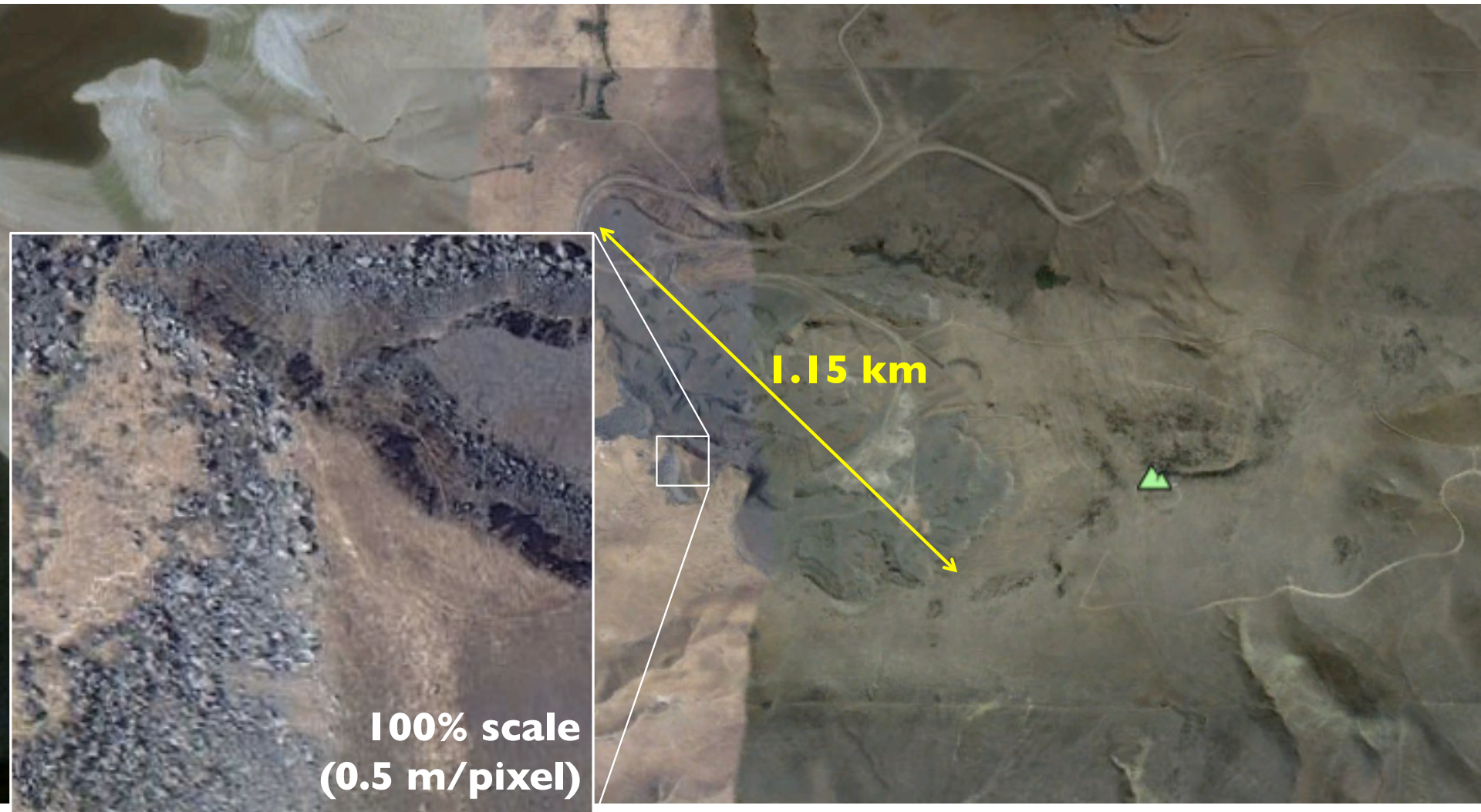
Jakobshavn Glacier, Greenland

- 6 input images
- 2500 km² coverage
- 5 m/post



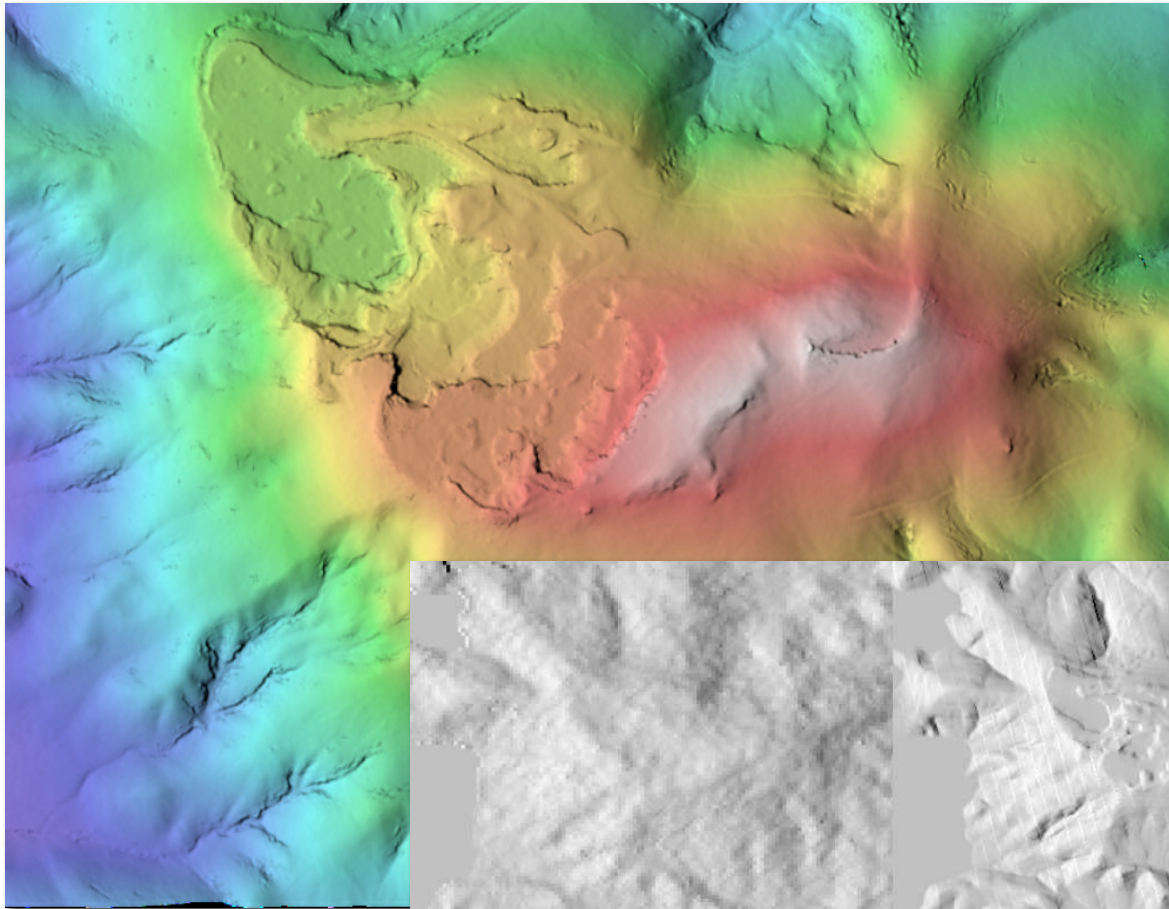
ASP for Earth

Non-vegetated areas



ASP for Earth

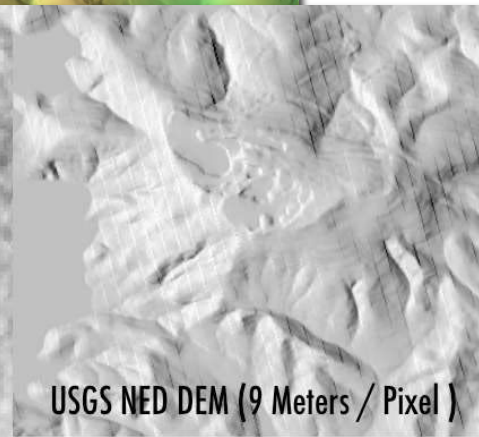
60% success rate processing Digital Globe stereo pairs without human input



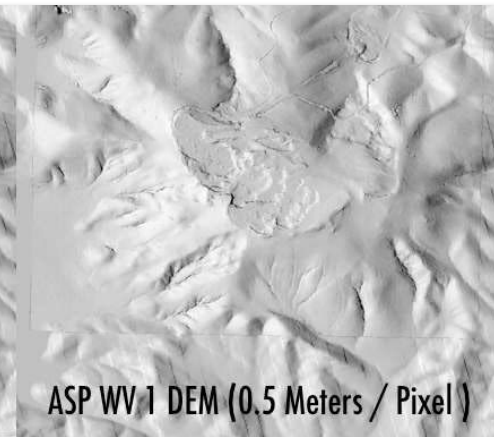
- Colorized DEM of the Basalt Hills Quarry
- Used for planetary rover analog testing
- Based on DigitalGlobe WorldView imagery



SRTM DEM (~ 31 Meters / Pixel)



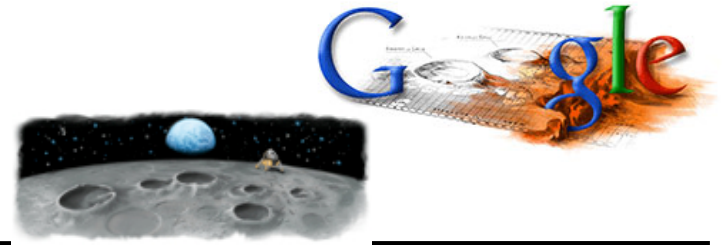
USGS NED DEM (9 Meters / Pixel)



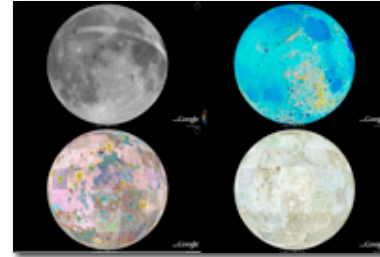
ASP WV 1 DEM (0.5 Meters / Pixel)

NASA / Google

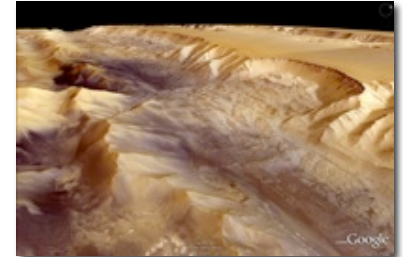
Explore the Moon and Mars in 3D



- “Google Moon” & “Google Mars” provide data availability & fusion for planetary data
- Includes “live” imagery of Mars from the THEMIS camera (appears on-line 2-4 days after downlink)
- Guided tours of the Moon and Mars narrated by Buzz Aldrin, Jack Schmitt, Ira Flatow, and Bill Nye.



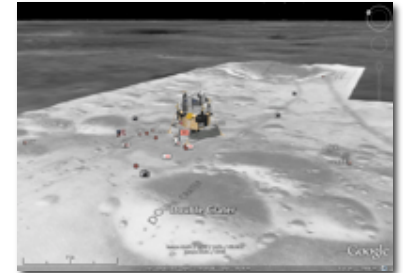
Modern / Historical Base Maps



High Resolution 3D Terrain



Geospatial Image Browsing/Indexing

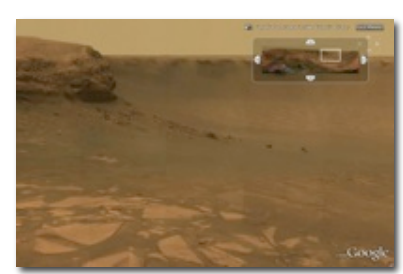


Tours Narrated by Notable Scientists and Astronauts

Try it for
yourself in
Google
Earth 5.0!



Geologic Maps



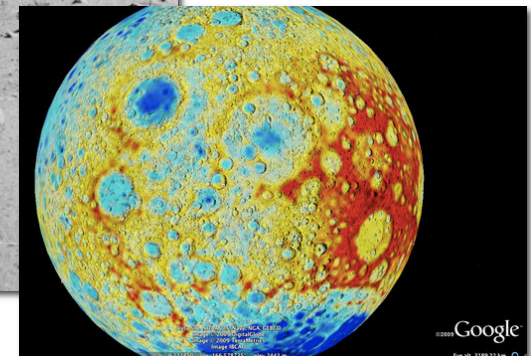
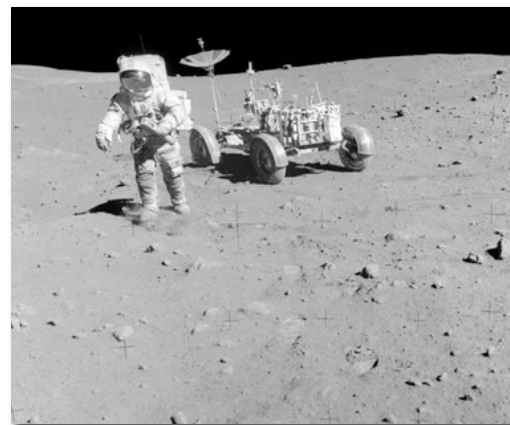
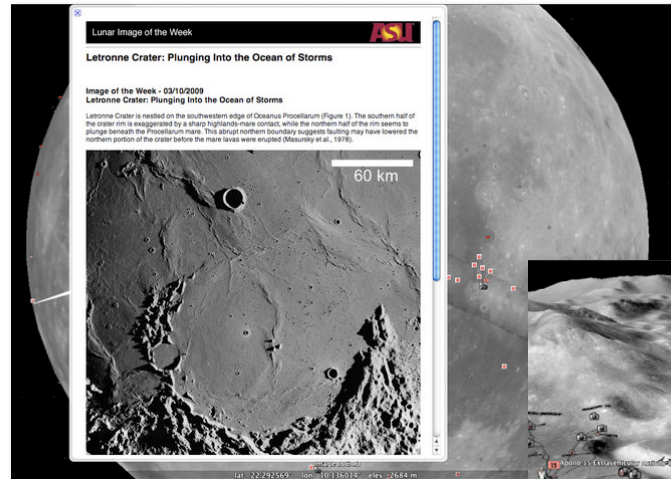
Geo-located Panoramic Imagery

Google Moon

Released July 20, 2009

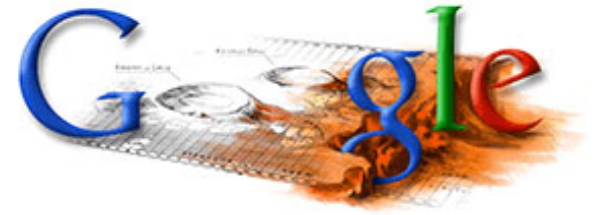


- “Moon for Google Earth”
 - Co-developed with Google
 - IRG created content, processing scripts, and base maps
 - Built in to Google Earth 5.0
- Content
 - Global maps: topography, geologic, historical, etc.
 - Spacecraft imagery: Apollo, Clementine, Lunar Orbiter
 - 3D models of spacecraft, landers, and crew rovers.
 - Tours (Andy Chaikin, Buzz Aldrin and Jack Schmidt)
 - And much more ...

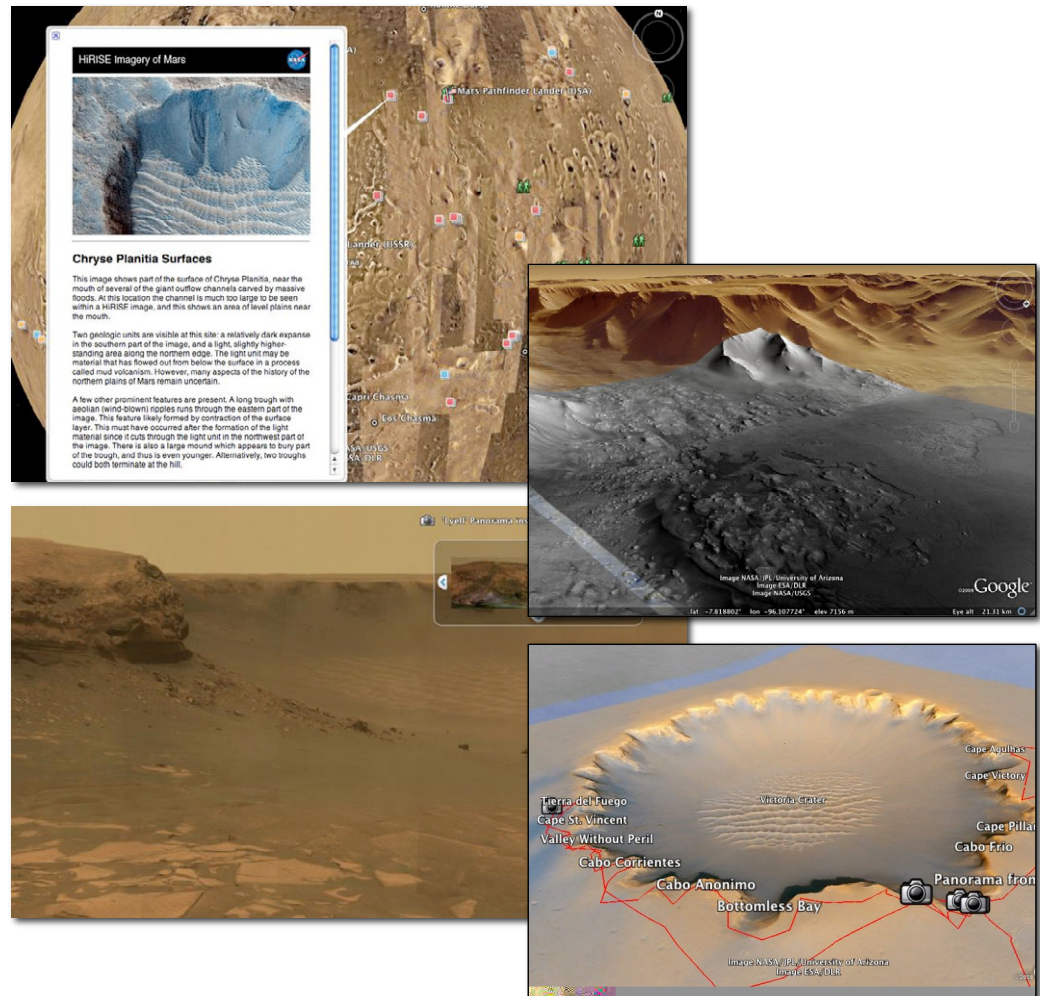


Google Mars

Released February 2, 2009



- “Mars for Google Earth”
 - Co-developed with Google
 - IRG created content, processing scripts, and base maps
 - Built in to Google Earth 5.0
- Content
 - Global maps: topography, infrared, historical, etc.
 - Imager footprints & overlays: HiRISE, CTX, MOC, etc.
 - MER tracks & panoramas
 - Tours (Bill Nye & Ira Flatow)
 - Live from Mars: THEMIS images within hours
 - And much more ...

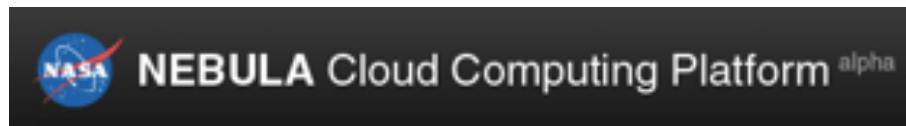


NASA / Microsoft

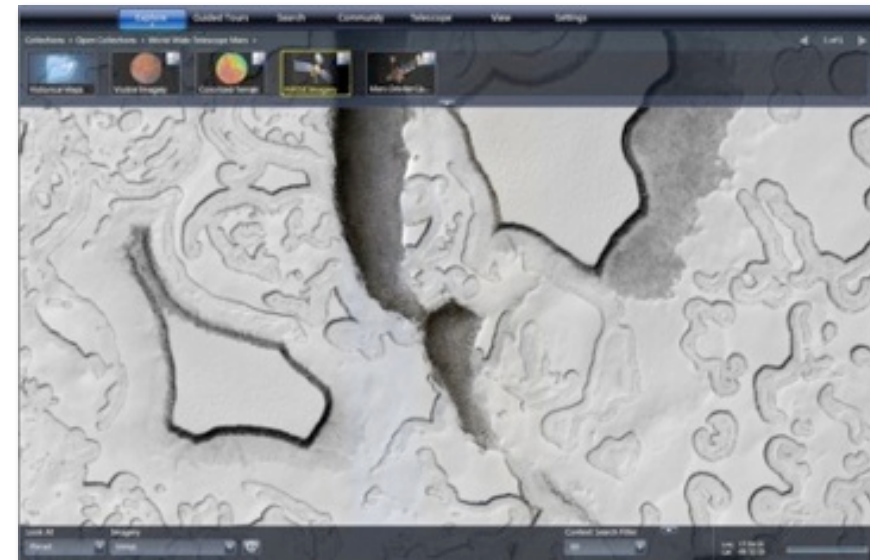
Bringing the Mars experience to WorldWide Telescope



- Featuring the largest digital image mosaic of Mars ever created
- Data sets for WWT Mars were created using the NASA Nebula cloud computer
- Guided tours of Mars narrated by Dr. Carol Stoker and Dr. Jim Garvin



<http://worldwidetelescope.org>



INPUT
OUTPUT

MOC

HiRISE

Total # of images	74,359	13,342
Pixels / Image	16 Megapixels	1.25 Gigapixels

Total Image Tiles	~38 Million	~526 Million
Total Mosaic Size	843 Gigabytes	12 Terabytes

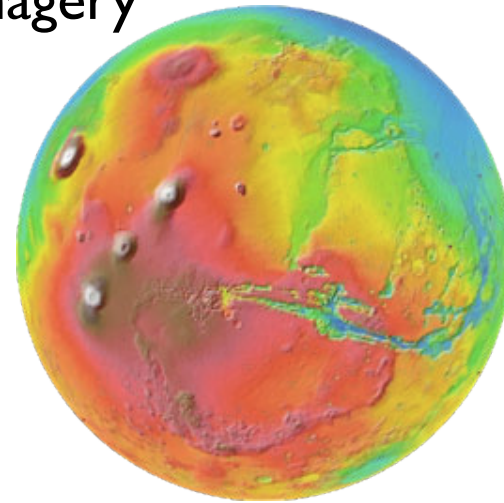
This work was done at ARC under a reimbursable space act agreement (RSAA).
The RSAA does *not* imply exclusive access to NASA data or to our team.

WWT Mars Base Layers

New global maps and historical imagery

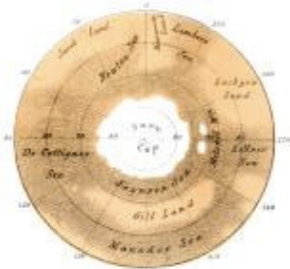
Global Imagery

Color MDIM v2
(merged w/ MOC-
WAC mosaic)

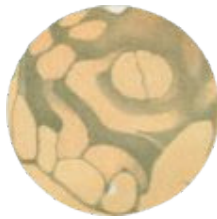


Mars Topography
(MOLA)

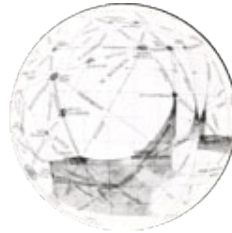
Historical Imagery



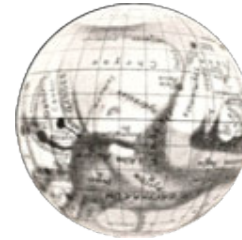
Nathaniel Green
(1877)



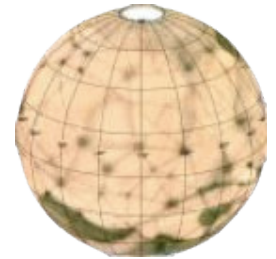
Giovanni Schiaparelli
(1890)



Percival Lowell
(1896)



Eugene Antoniadi
(1909)

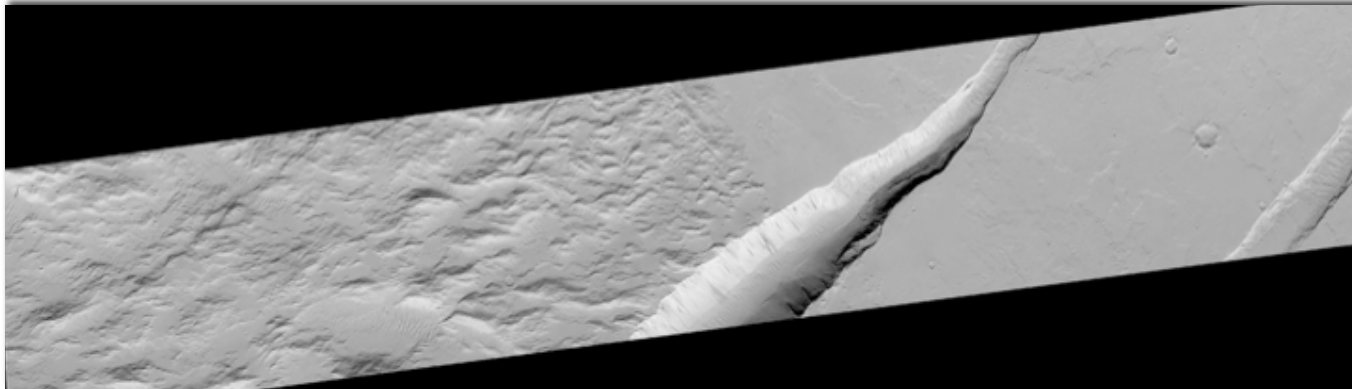


MEC-I Prototype (USAF)
(1962)

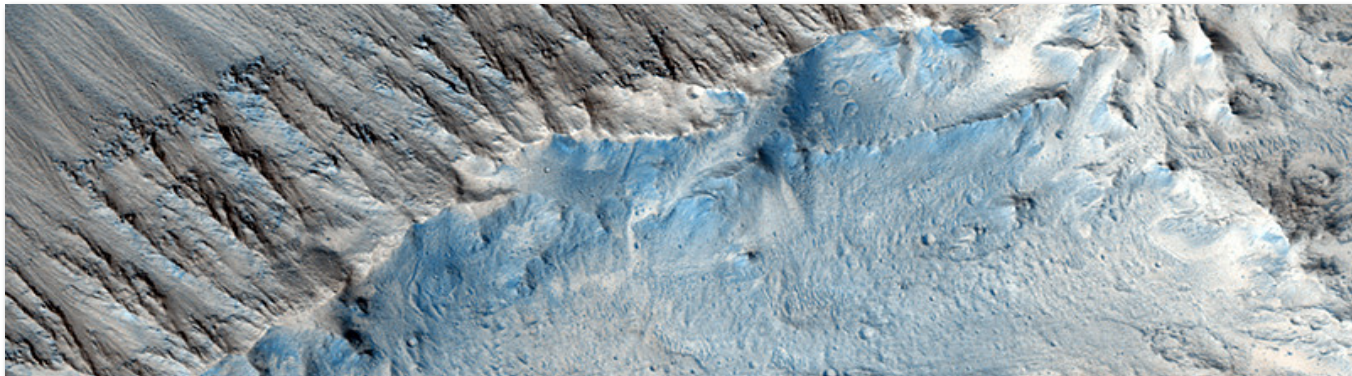
WWT High Resolution Layers

From Mars Global Surveyor and Mars Reconnaissance Orbiter

74,359 Mars Global Surveyor MOC Images



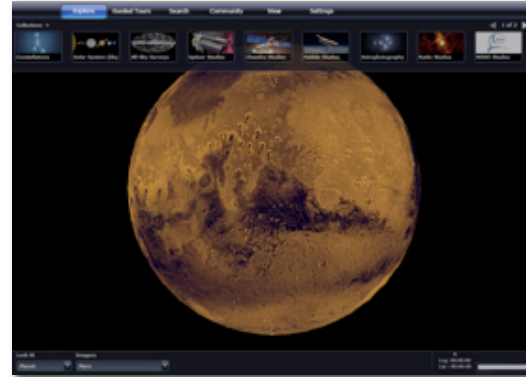
13,342 Mars Reconnaissance Orbiter HiRISE Observations



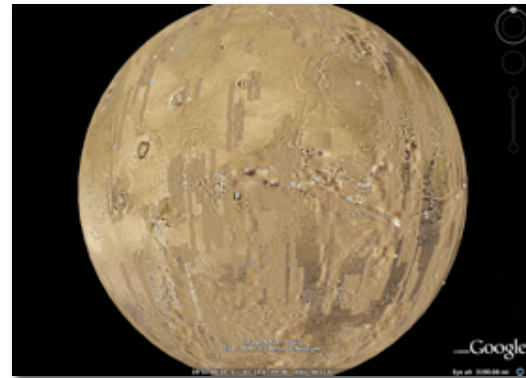
Access to Planetary Data

Providing 2D and 3D NASA imagery to cutting-edge geo-browser platforms

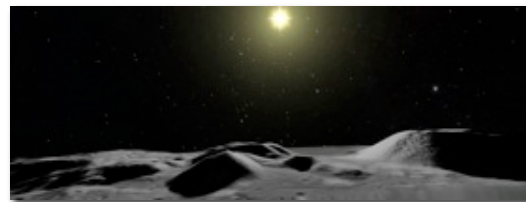
- NASA has done an exemplary job of archiving its data and making it publicly available (e.g. the PDS and DAACs), but these archives were not designed for **immediate, on-demand access** to the data.
- We believe that there is a need to bridge the gap between the PDS and users who are not “**data experts**.”
- Ubiquitous, **freely available geo-browser** platforms are technologically well-suited to this task, and a natural fit to fill this gap.



Microsoft
WorldWide
Telescope
(WWT)



“Google Moon” &
“Google Mars”
(in Google Earth 5.0)



Lunar Imagery
for Uniview

Live Data into Google Earth

Continuous, automatic data release

Mission Instrument Team Provides

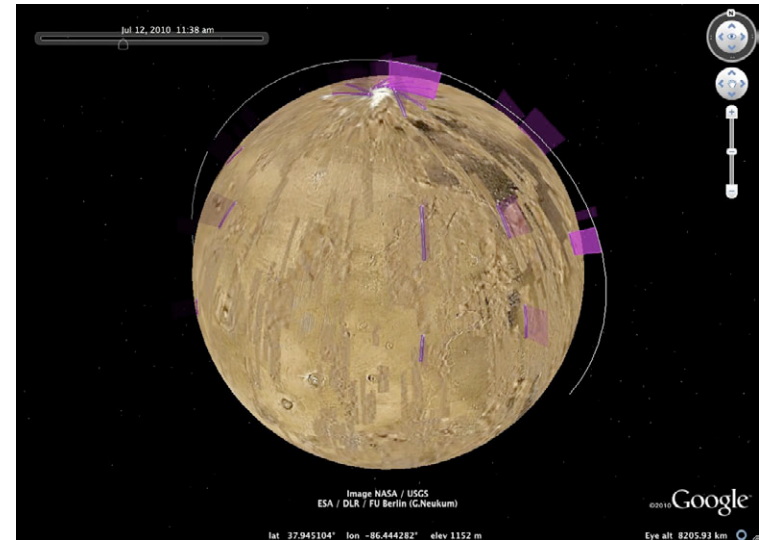
(via public or private URL)

Spacecraft Orbit
lon, lat, alt, time (CSV file)

Data Footprint
lat,lon of vertices (CSV file)

Instrument data
(ISIS cube, PNG, JPEG, etc.)

data pull
(periodic)



publish to
Google Earth

KML Convert

(using ARC Neo-Geography Toolkit)